KEI
Research Report
2024-01

Analysis of Low-Energy Demand Scenarios with Global CGE Model

글로벌 CGE 모형을 활용한 저에너지 수요 시나리오 연구

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Publisher	Lee, Changhoon
Published by	Korea Environment Institute 370 Sicheong-daero Sejong-si, 30147, Republic of Korea Tel: +82-44-415-7777, Fax: +82-44-415-7799 http://www.kei.re.kr
Publication Date	March 2024
ISBN	979-11-5980-936-1

Foreword

As efforts to achieve Nationally Determined Contributions (NDC) goals and accelerate the net-zero transition are accelerating worldwide, interest in lowering energy demand is growing. In Korea, while strengthening policies to improve energy efficiency in industries, the government has designated Energy Consumption Reduction and Carbon-Neutral Practices as one of the 12 key tasks in the Basic Plan for Carbon-Neutral Green Growth, and continues to strengthen demand-side policies.

This study quantitatively examined the potential for reduced energy demand in global mitigation efforts using a global Computable General Equilibrium (CGE) model. It analyzes how low energy demand measures alleviate the economic burden of greenhouse gas (GHG) reduction efforts in Korea and worldwide. The study was conducted in collaboration with researchers at the International Institute for Applied Systems Analysis (IIASA), a well-known research organization that has been actively conducting research on energy demand reduction. The results of this study are expected to make a meaningful contribution to the academic literature, and inform improvements in energy demand policies, not only in Korea but also globally. Furthermore, this study could serve as a basis for continued collaboration with international research institutes.

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Executive Summary

1. Research Background and Objectives

❑ Increasing global attention to energy demand

- ○ Global studies, such as the IPCC Sixth Assessment Report (AR6) and Network for Greening the Financial System (NGFS) Phase 4, have emphasized demand-side responses.
  - The IPCC AR6 has a separate chapter on demand, emphasizing demand-side responses and their potential to contribute to GHG reduction.
  - As one of the Illustrative Mitigation Pathways (IMP), the IMP-LD pathway, which considers low-demand measures such as an efficient use of resources, is presented.
- ○ Demand-side responses, such as energy efficiency and behavior change, are expected to be a cost-efficient and effective way to reduce GHG emissions and reduce the burden on the supply-side, especially Carbon Capture and Storage (CCS).
- ○ Quantitative analysis of low energy demand scenarios is necessary, as energy demand may be given more prominence in the IPCC 7th Assessment Report (AR7) and national policies are focusing more on the economic and environmental benefits of demand-side responses.

❑ Develop low energy demand scenarios and quantitatively analyze the potential for low energy demand measures to contribute to domestic and global GHG reductions through global CGE models

- ○ The study identifies low energy demand measures for industries and households that are considered in literature and policy and reflects them into the global CGE model, enabling a comprehensive analysis of the impacts of low energy demand scenarios both domestically and globally.

- The study develops a global CGE model that can analyze the temperature increase and resulting energy demand changes due to global GHG emissions, and it is expected to be used for various domestic and global GHG mitigation policies or scenario analysis.
- Through research collaboration with the International Institute for Applied Systems Analysis (IIASA), we expect to establish a network and identify potential research topics for research collaboration, thus establishing a foundation for concrete research collaboration.

2. Research Trends in Energy Demand and Modeling Analysis

2.1. Literature on Energy Demand and Modeling Analysis

❏ Research on the development of low demand scenarios

- Grubler et al. (2018) presented a narrative of the low energy demand scenario on which many low demand scenarios have been built.
- IPCC AR6 presented the IMP-LD scenario as one of the IMPs, and NGFS Phase 4 also presented a low demand scenario. This indicates an increased interest in low demand globally.
  - The IMP-LD in IPCC AR6 emphasized the efficient use of resources, including energy, and the transition of consumption patterns and was characterized by less use of Bioenergy with Carbon Capture and Storage (BECCS) than other IMPs.
  - From NGFS Phase 4, the Low Demand scenario leads to the low levels of physical and transition risks among all seven scenarios.

❏ Research is also underway to analyze the potential of low demand.

- IPCC AR6 had a separate chapter on demand and reviewed the Avoid, Shift, and Improve (ASI) of final energy demands.
  - It emphasizes the potential of demand-side approaches for reducing GHG emissions by 40–70% in the building, land transport, and food sectors by 2050.
- The World Economic Forum (2024) also emphasized the importance of shifting

energy demand, highlighting that action on energy demand could reduce energy consumption by 31% by 2030, with an annual impact of USD 2 trillion.

- Low awareness, insufficient returns on measures and instruments to reduce demand, and a lack of policy support obstruct the facilitation of energy demand reduction.

○ Research is being conducted on demand policies and measures for key sectors, such as building, transport, and energy as well as energy efficiency improvement, and changes in energy consumption behaviors, using various sectoral models, econometric methods, and statistical analyses.

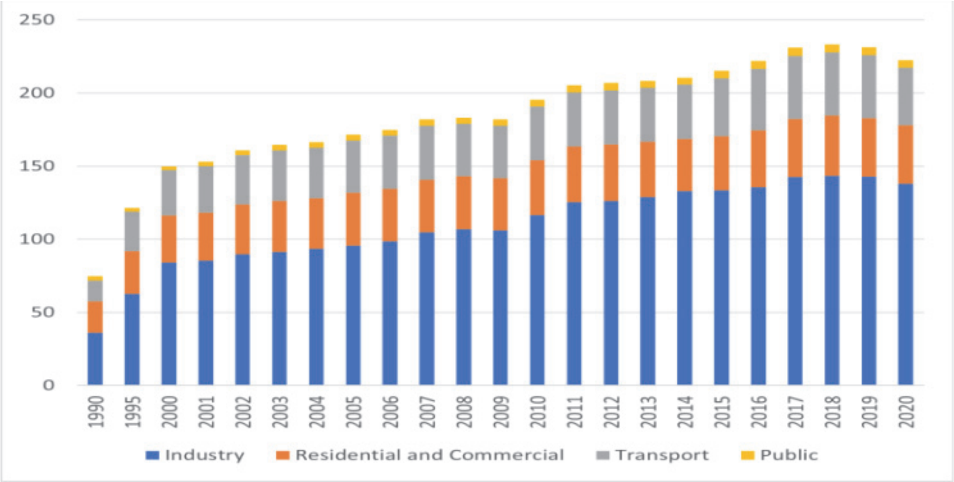
2.2. Review of Energy Status and Demand-side Policies

❑ Brief energy status in the Republic of Korea

○ The Republic of Korea is a major energy importer, with dependence on energy imports of 94% in 2022, and there has been much interest in energy demand from the perspectives of energy supply and demand balance and energy security.

- Final energy consumption was ranked 10th in the world at 181.7 MTOE in 2021, with oil and natural gas imports ranked 5th and 6th in the OECD, respectively.
- Regarding the final energy consumption by sector, the industrial sector accounts for 63.3%, followed by the transportation and residential/commercial sectors with 16.9% and 17.4%, respectively (2021, Energy Balance TOE) (KEEI, 2022, pp.280-285).

Figure ES 1. Final energy consumption by sector



Source: KESIS (November 15, 2022), "Final Energy Consumption by Sector (Annual, Calorie-based)", accessed on January 2, 2024.

- ㅇ Domestic final energy consumption is expected to continue to grow at an average rate of 0.8% annually from 2022 to 2027.
- ㅇ Economic and technological changes such as the introduction of AI and ICT and the expansion of electric vehicles, as well as changes in demographics such as low birthrates and an aging population, are likely to affect the composition and projections of future energy consumption.

❑ Energy demand policies of Korea

- ㅇ Continuing efforts to improve energy efficiency in industry, households and commercial buildings, and transportation through the "Comprehensive Plan for Market-Based Energy Demand Efficiency"
- ㅇ Various policies focused on improving energy efficiency, including voluntary agreements, have been implemented.
  - The Energy Use Rationalization Act has driven energy efficiency improvements since the 1970s, including those in energy-intensive sectors.
  - The KEEP 30 program is an agreement between the government and 30

energy-consuming companies to provide incentives for achieving energy efficiency improvements between 2023 and 2027, aiming for an average annual improvement of at least 1% over five years.

- Efforts to improve efficiency continue in the transport sector, including the introduction of electric vehicle labeling and fuel economy standards for medium- and heavy-duty vans and cargo vehicles. Policies are also being introduced to improve building efficiency.

○ Besides improving energy efficiency, policies are being established to change society, including policies for bringing about long-term changes, such as establishing a foundation for education, sharing information, and facilitating communication.

- Efforts are being made to change behavior, such as recommended temperatures for heating and cooling in buildings, energy saving campaigns, and sharing carbon-neutral practices.
- For example, the Energy Cashback Program offers incentives to residential electricity customers to reduce their electricity consumption by 3% or more compared to the same month in the previous two years to encourage behavioral change.

○ Efforts to improve efficiency and reduce energy demand in the industry, building, and transportation sectors are expected to ease the burden on the supply-side, including CCS, renewables, and other low-carbon technologies.

❑ Energy demand-related policies in the EU and Germany

○ Europe is actively adopting policies to reduce energy consumption to maintain stable energy supplies and imports, accelerate the achievement of EU climate goals, and address energy price volatility, also during the Russia-Ukraine War.

○ As part of "REPowerEU", the "EU Save Energy Plan" is proposed to support energy consumption reductions in the EU.

- This plan supported increased use of public transportation and efficient appliances, and encouraged reducing the use of cooling devices.
- It includes enhanced rules on the energy performance of buildings and energy audits.

- The "2023 Energy Efficiency Directive" proposed an enhanced energy efficiency target to further reduce energy demand by 11.7% relative to the 2020 reference scenario by 2030.
  - The directive sets the target to reduce primary energy consumption and final energy consumption by 40.5% and 38%, respectively, by 2030.
  - The directive proposed that EU member states set their own targets, such as energy intensity and energy consumption reductions, objectively based on the national circumstances affecting energy consumption.
- The "Energy Efficiency First" Principle in the revised Energy Directive is to establish the legal ground for policy and investment decision-making, which prioritizes energy efficiency improvement and production cost reductions.
  - The principle of "Energy Efficiency First" can (1) reduce the level of investment necessary for the transition towards renewables through energy demand reduction, (2) support the sustainable use of limited resources, and (3) enhance the resilience of the EU energy system.

Table ES 1. The energy efficiency first principle in EU legislation

Requirement 1	Applying cost-benefit assessment methodologies, including the assessment of the benefits of energy efficiency measures
Requirement 2	Identifying an entity, which take responsibility of monitoring the application of the principle
Requirement 3	Reporting the application of the principle to the Commission

Source: European Commission (December 24, 2023), "Energy Efficiency First Principle", accessed on January 11, 2024.

- Germany has been promoting long-term and significant energy demand reductions for energy transition and climate response, going even further than the EU's target.
  - The "New Energy Efficiency Act" sets long-term targets for energy consumption reductions in both public and private sectors (26.5% reduction by 2030 from the 2008-level).
  - Companies consuming 15 GWh or more annually require the establishment

of an energy or environmental management system.

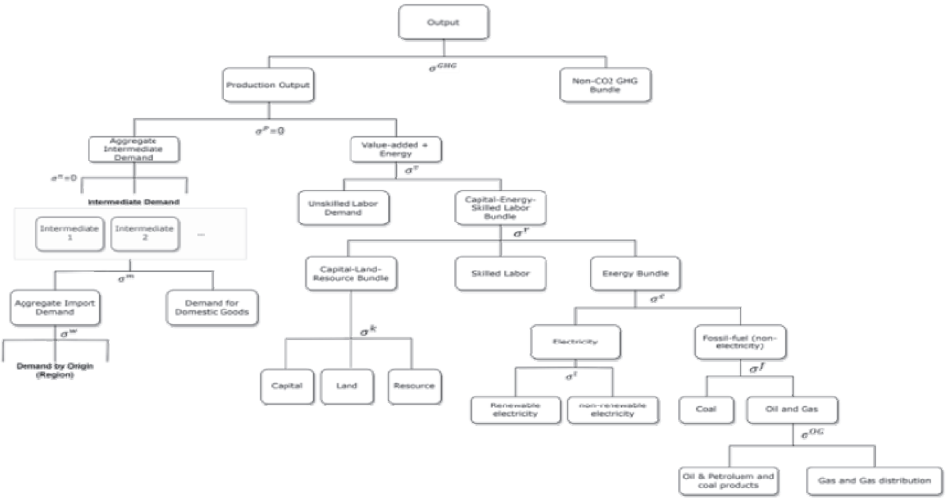
- The "2023 Climate Action Program" of Germany includes various energy efficiency improvements and energy consumption measures.

3. Development and Update of the Global CGE Model

❏ Structure of the global CGE model

- The model applied the latest GTAP 11 Power Database, which included 76 sectors, including detailed information on 12 power technologies, and covered 160 countries and regions.
- The study consolidated data from 76 sectors into 21 aggregated sectors and grouped 160 countries and regions into 17 aggregated regional categories.
- The model covered six major GHG emissions (N_2O, CH_4, NF_3, SF_6, PFCs, and HFCs) and applies updated SSP scenarios from the EU Navigate project for calibration.
- The global CGE model was adopted for the capital dynamic structure, which differentiated "old" and "new" capital with different elasticities of substitutions.

Figure ES 2. Production nesting structure



Source: The authors.

❑ Development of a climate module and application of a damage function for additional cooling and heating energy consumption

- The model adopted a climate module from the FUND model to analyze the energy consumption changes due to global and regional temperature change.
  - The climate module of the FUND model calculated the atmospheric carbon dioxide concentration, radiative forcing, and global mean temperature changes.
  - Six major GHG emissions were calculated using the global CGE model, and this information was fed back into the climate module to calculate the global mean temperature change.
- The damage function for additional cooling and heating energy consumption in the FUND model was applied to the model to analyze the impacts of climate change on energy demand.
  - The global mean temperature change was calculated using the climate module, and the CGE model determined the additional energy consumption for cooling and heating due to the temperature change.
- The additional cooling and heating energy consumption was calculated and reflected in the global CGE model by adjusting the share parameter of the energy-capital-skilled labor bundle.

❑ Applying the constraints on household's energy consumption

- To reflect the constraints on household energy consumption, the study adjusts the share parameter of electricity and energy bundle.
  - The share parameters of energy and electricity consumption shrank at a pre-specified rate (1.25% per year for Global South and 1.5% per year for Global North).
  - The study assumed that there may be a relatively high consumption shift in energy sources to other commodities in the Global North, considering changes in activities in end-use services of 'consumer goods' and energy demand from Grubler et al. (2018).

4. Development of a Low Energy Demand Scenario

❑ Key components of a low energy demand scenario

- With consideration of the findings from the literature review and the structure of the global CGE model, five key components were selected for establishing a low energy demand scenario.
  - The five components were: (1) Autonomous Energy Efficiency Improvement (AEEI) in industry and household consumption; (2) energy consumption changes due to climate change; (3) lifestyle change; (4) carbon pricing; and (5) the impact of COVID-19.

❑ Structure and assumptions of a low energy demand scenario

- The rates of AEEIs were determined region-wise (Global North and Global South).
  - Owing to the relatively high level of energy efficiency in the Global North and the relatively high potential in the Global South, the AEEI improved by 1.5% per year in the Global South and by 1% per year in the Global North.
- Changes in heating and cooling energy consumption calculated from the FUND model were reflected in the capital-energy-skilled labor bundle.
  - The climate module and damage function of energy consumption from the FUND model in the global CGE model calculated additional heating and cooling-related expenditure.
- Electrification with further deployment of renewables was considered.

  - The learning rate for renewable electricity was applied to accelerate the deployment of renewable electricity, which indirectly reflected the acceleration of the energy transition towards renewables.
- ○ The exogenous constraints on households' energy consumption were applied.
  - The low demand scenario considered behavioral changes in people and households by reducing the energy consumption of households in the Global North and Global South by 1.5% and 1.25% per year, respectively.
- ○ The study adopted the exogenous carbon pricing scenario from the NGFS Phase 4 Net Zero 2050 Scenario (REMIND-MAgPIE model).
  - The global CGE model did not include advanced technologies such as CCS, DAC, and hydrogen; therefore, it was difficult to directly reach Net Zero.
  - Instead of setting the carbon-constraining scenario, carbon prices in 2030, 2040, and 2050 from the NGFS Net Zero 2050 Scenario (REMIND-MAgPIE model) were considered in the scenario analysis.

❑ Scenario setting

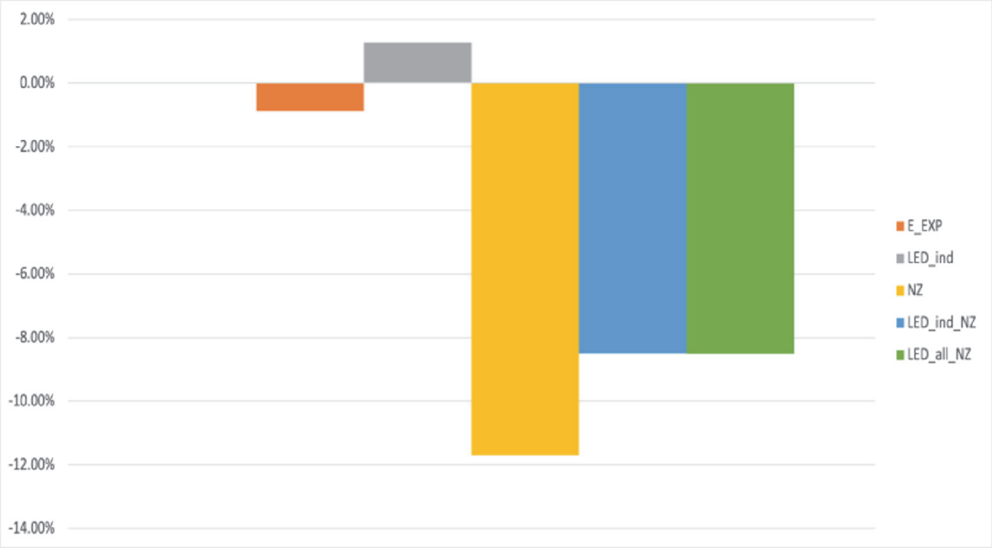
- ○ Six scenarios were set to analyze the low energy demand: Business-as-Usual (BAU); BAU with energy expenditure (E_EXP); low energy demand in industry (LED_ind); net zero carbon pricing (NZ); low energy demand in industry with NZ (LED_ind_NZ); and low energy demand in industry and household with NZ (LED_all_NZ).
  - Business-as-Usual (BAU) scenario is the baseline scenario, which follows the updated SSP2 scenario.
  - The E_EXP scenario is the BAU scenario with cooling and heating energy demand changes resulting from temperature changes.
  - The LED_ind scenario considers energy efficiency improvement in industrial sectors besides the E_EXP scenario.
  - The NZ scenario is the E_EXP scenario, with Net Zero carbon pricing from the NGFS Net Zero 2050 scenario.
  - The LED_ind_NZ follows the NZ Scenario's emissions pathways and additionally considers energy efficiency improvements in industrial sectors.
  - The LED_all_NZ scenario also follows the NZ scenario's emissions pathways and considers the energy efficiency improvement in industrial sectors and households and the constraints in household energy consumption.

5. Results and Policy Implications

❑ Results: Global

- Global temperature increases and energy efficiency improvements can have positive impacts on energy demand and GHG emissions.
  - The global mean temperature could rise beyond 2℃ in the next few decades if there is no strict carbon pricing or mitigation action.
  - Some positive cooling and heating energy demand changes are expected owing to global mean temperature increases.
  - The study found rebound effects of energy efficiency improvement in that the industrial sectors' energy efficiency improvement led to an increase in the final energy demand relative to the BAU level.
- NZ scenario can reduce GHG emissions and final energy demand significantly. Simultaneously, carbon pricing can lead to substantial economic losses.
  - NZ scenario could lead to GDP losses of 11.7% from to 2021–2050 relative to the BAU level.
  - At the sectoral level, fossil fuel sectors, particularly coal and gas, could experience substantial negative impacts, and their production could reduce by about 38%–59% (2021–2050) relative to the BAU level.
- With carbon pricing, energy efficiency improvements in industry and households and household energy consumption reductions can contribute not only to further reducing final energy consumption but also to alleviating the economic burden of GHG mitigation.
  - Additional measures for improving energy efficiency and reducing household energy consumption could reduce the final energy demand by more than 30% below the BAU level.
  - Global GDP losses could exceed 11% relative to the BAU level with net-zero carbon pricing, but low energy demand measures could reduce global GDP losses to 8.5% relative to the BAU level.
  - Low demand measures could bring better results in production and investment in non-fossil fuel-related sectors compared to the NZ scenario.

Figure ES 3. Changes in global real GDP (2021–2050) (relative to BAU)

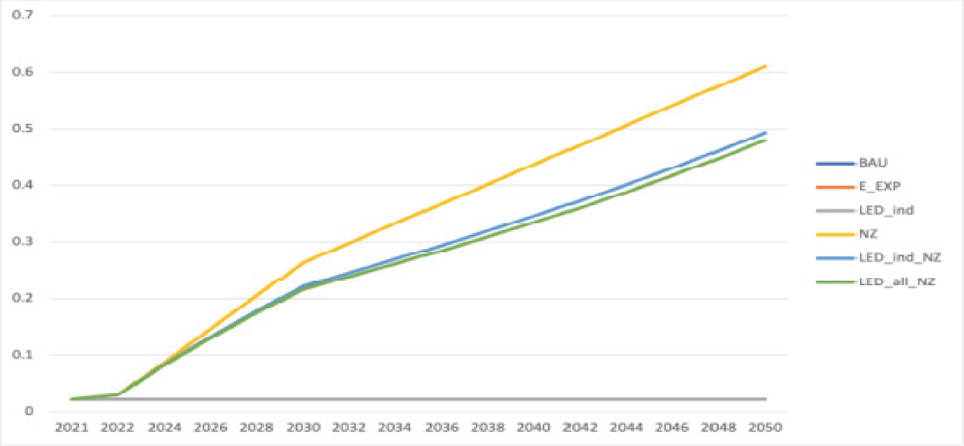


Source: The authors.

❑ Results: Korea

- Global temperature increases could slightly raise cooling and heating energy demand, but their impacts on GHG emissions are minimal.
- Similar to the global results, low energy demand measures could reduce the negative economic impacts of mitigation actions.
  - Low energy demand measures could lower the economy-wide carbon prices required to meet the same level of emission reductions in the net-zero scenario.
  - NZ scenario indicates USD 610 per tCO_2eq in 2050, but the LED_all_NZ scenario needs USD 480 per tCO_2 eq in 2050 to meet the same level of GHG emissions reductions.

Figure ES 4. Carbon price trajectories by scenario (2021-2050)



Source: The authors.

- Net zero transition could lead to slight losses of 6.88% in real GDP (2021–2050) relative to the BAU level, but low energy demand measures could reduce the GDP losses by approximately 1.86%–1.92% relative to the BAU level.

○ For sectoral production, net zero carbon pricing would increase the production of renewable and nuclear electricity significantly, but it would decrease fossil-fuel-related production.

- In Korea, the model suggests that there can be a relatively substantial increase in nuclear electricity production compared to renewable electricity production.
- Low energy demand measures with net zero carbon pricing can reduce production and investment losses in non-energy-related sectors.

❑ Sensitivity analysis: Accelerated Low Energy Demand Scenarios

○ Two additional scenarios, assuming accelerated actions, were considered to explore the potential of low demand measures.

- The Accelerated Low Energy Demand Scenario (ACC_LED_NZ) indicates accelerated efforts for energy efficiency improvement in industry and households and energy consumption reductions in households. Energy efficiency improvements have accelerated in the Global North and Global South to 1.5% and 1.75% per year, respectively, and household energy consumption reductions have accelerated to 1.5% in the Global South and 1.75% in the Global North.

- The Accelerated but Delayed Low Energy Demand (ACC_delayed_LED_NZ) scenario assumes that accelerated actions will begin after 2035; until then, this scenario follows the LED_all_NZ scenario.

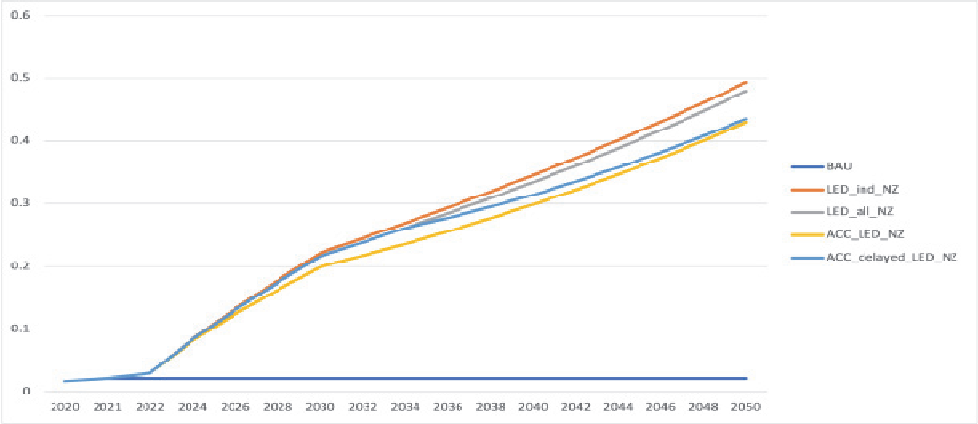
○ Accelerated actions could reduce global final energy demand and global GDP losses.

- Accelerated actions can reduce final energy demand and GDP losses relative to the LED_all_NZ scenario. Accelerated actions could reduce GDP losses (2021–2050) by 7%–8%, relative to the BAU level, down from 8.5% in the LED_all_NZ scenario.
- The general trends of global production and investment in the accelerated scenarios are similar to those of LED_all_NZ, and the aggregate losses of global production and investment decrease slightly under the accelerated scenario.

○ Accelerated actions could bring more considerable economic gains to Korea compared to the Net Zero with low energy demand scenario.

- Carbon prices required to follow the Net Zero emission pathway become lower than net zero under low energy demand scenarios.
- Compared to the carbon prices of USD 610 (NZ) and USD 480 (LED_all_NZ) per tCO_2eq in 2050, accelerated LED scenarios require USD 430 ~ USD 435 per tCO_2eq in 2050 to achieve the same level of GHG mitigation.

Figure ES 5. Carbon price comparison (Net Zero with/without Accelerated Actions)



Source: The authors.

- Accelerated actions have more positive impacts on production and investment in Korea than Net Zero with low energy demand measures.
- At the sectoral level, accelerated actions lead to slight production gains in many non-energy sectors compared to the sectoral production under Net Zero with low energy demand measures.

❑ Policy implications

- ㅇ Global warming could lead to a slight increase in GHG emissions and final energy demand, but its impacts vary by region.
- ㅇ Low energy demand measures accompanied by carbon pricing could bring synergistic effects and achieve mitigation in more efficient and effective ways.
  - Energy efficiency improvement and household energy consumption reduction alone have a limited impact on mitigation and final energy demand reduction.
- ㅇ The transition of industrial sectors with high energy use and GHG emissions is key for achieving low energy demand and net-zero transitions.
  - The study provided evidence that improving energy efficiency in industrial sectors can support the net-zero transition and contribute to a low-demand future.
  - 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.
  - Encouraging innovative technologies and industries can lead to positive economic outcomes.
- ㅇ A transition towards low energy demand can be beneficial in terms of the 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. Hence, 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 a low-demand lifestyle could alleviate the economic burden of households by reducing expenditure on energy commodities.
- ㅇ Further study mainly suggests improving the current global CGE model and enhancing the utilization and management of databases.
  - For a rigorous study of net-zero, advanced low-carbon technologies such as CCS, DAC, and hydrogen should be included in the model.
  - To address both individual and group demand-side measures and their economy-wide potential, the integration of top-down and bottom-up models such as MESSAGEix, GCAM, and REMIND-MAgPIE is necessary.
  - Transparent and standardized database management can facilitate collaboration with other research institutes and communities.
  - Collecting behavioral information from individuals and households, such as real-time energy consumption data and the social and economic drivers of energy consumption, will become increasingly important.

❑ Potential research topics related to energy demand

- ㅇ Circular economy, material cycles, and their impacts on energy demand
  - Recently, the MESSAGEix-GLOBIOM model framework included MESSAGEix-Materials, which facilitates the linkage between industrial energy and material demand and production.
  - With the growing importance of the circular economy in future transformations,

the demand for building IAM scenarios with tighter linkages to circular economy measures will increase.

- To investigate the future role of circular economy measures, the global CGE model could be further developed to incorporate detailed material-related variables from MESSAGEix.

○ Linking the existing demand narratives

- Several modeling teams have developed scenarios around narratives of demand changes following the ASI, and MESSAGEix have developed scenarios based on more detailed demand modules.
- Given the bottom-up nature of these scenarios, the existing demand narratives can provide better insights into the necessary sectoral formations.

○ Just Transition and its impacts on employment and other well-being indicators

- Given the multidimensionality of well-being issues, a recent study shows that a demand-focused transition can be more beneficial to human well-being when carefully implemented.
- CGE-based models can provide further insights into the economy-wide effects of mitigation or demand-focused transition scenarios that process-based IAMs such as MESSAGEix cannot cover.
- The IIASA's recent internal project, "Just Transition for All", develops additional indicators for well-being assessment of mitigation scenarios.

6. Conclusion

☐ Key contributions of the study

○ Understanding of the trends in low energy demand scenario discussions and model developments

○ The study improves a global CGE model to analyze the impacts of global warming on energy demand, as well as the economic impacts of low energy demand scenarios.

- While much of the literature has analyzed the impacts of activity levels or interventions, there has been little analysis of the aggregate economic impacts of low energy demand scenarios.

- ○ The study can contribute to providing a basis for establishing and expanding domestic demand policies, such as demand efficiency and nationwide awareness on energy demand measures.

❑ The implications of the low demand scenario analysis

- ○ The implementation of carbon prices could have negative economic impacts on GDP and industrial production and investments, particularly in fossil-fuel-related sectors.
- ○ There can be significant transitions among industries, highlighting the need for policies to facilitate such transitions. An increased focus on Just Transition as well as the development of technologies and policies to accelerate the transitions would be necessary.
  - As production and investment in existing fossil-fuel-based or energy-intensive industries decline, job losses and stranded assets will increase.
  - Significant policy responses, such as retraining programs, policies to reduce stranded assets, and support for local economies around fossil fuel and energy- and emission-intensive industries, would be required.
- ○ It is necessary to emphasize the need for energy demand policies, which could reduce the economic burden of the transition.
  - In addition to carbon pricing, the introduction of low energy demand measures could lower the carbon prices required to achieve the same level of emission reductions.
  - Low energy demand measures could bring positive impacts not only on real GDP but also on production and investment in non-energy sectors, in general.
- ○ Energy demand policies have the potential not only to reduce the socio-economic impacts of the transition towards carbon neutrality but also to contribute to reducing the burden on the supply side.
  - The significant role of energy efficiency improvements in the industrial sectors underscores the necessity for continuous efforts to enhance energy efficiency.
  - It is worth considering to introduce or design a principle like EU's Energy Efficiency First Principle, which explicitly reflects efforts and measures aimed at increasing energy efficiency in policy and investment decisions for sectors

affecting energy demand or energy systems.

  - It is crucial to support the adoption of innovative technologies.
  - Policies that incentivize behavioral changes and urban development plans which decrease energy consumption from the beginning could be considered.

- Further development of the model is required to conduct a comprehensive analysis of low energy demand scenarios.
  - The structural limitations of the model and the limited range of low energy demand measures should be addressed in future research.
  - Innovative technologies, such as CCS and hydrogen, as well as circular economy and material demand, should be included to analyze the net-zero transition
  - Linking the global CGE model with sectoral models will allow for the reflection of the individual or a set of low energy demand measures.
- Research cooperation with international research institutes, which possess expertise in modeling and scenario analysis, is necessary to facilitate low energy demand analysis and advance the model in efficient and effective ways.

Keywords: Global CGE Model, Energy Demand, Scenario Analysis, International Research Cooperation, Modeling

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Abbreviations and Acronyms

CGE	Computable General Equilibrium
SSP	Shared Socioeconomic Pathways
COP	Conference of the Parties
GST	Global Stocktake
IIASA	International Institute for Applied Systems Analysis
NZ	Net Zero
LED	Low Energy Demand
IAM	Integrated Assessment Model
BECCS	Bioenergy with Carbon Capture and Storage
EAF	Electric Arc Furnace
DRI	Direct Reduced Iron
GHG	Greenhouse Gas
GDP	Gross Domestic Product

1 Introduction

1.1 Research Background

There have been accelerated discussions on achieving the global 1.5 and 2℃ goals and reaching net zero, and it has become important to analyze the potential economic impacts of the net-zero transition based on global integrated models. Besides the Global Stocktake (GST) in 2023, as the 2030 NDC target year approaches, discussions on the feasibility of achieving the global 1.5 and 2 ℃ goals have accelerated.

In 2023, COP 28 in Dubai, UAE, discussed the first GST, which assessed the implementation of the Paris Agreement and indentified that a 43% reduction in greenhouse gas (GHG) emissions by 2030 and 60% by 2035 are required to achieve the 1.5℃ goal (UNFCCC, 2023, pp.11-15).1) It has become important to enhance the Parties' ambition to achieve an 84% reduction in GHG emissions compared to 2019 levels by 2050. A recent UN report analyzed the NDCs of 195 Parties, highlighting the challenges of achieving the 1.5℃ goal with the current NDCs alone.2) The current NDCs are projected to reduce emissions by only 2% compared to 2019 by 2030, which shows a significant gap from 43% reductions for achieving the 1.5℃ goal.3) This highlights the need for countries to step up their mitigation ambitions and efforts, and for a stronger policy drive to transition away from fossil fuels and expand renewable energy capacity.

Discussions on national and regional mitigation targets for achieving global temperature targets are highly likely to intensify in accordance with the GST results. By 2025, all countries will be required to prepare their 2035 NDCs, and the need

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1) Song et al. (December 28, 2023), "COP 28 Highlights and Takeaways", accessed on January 10, 2024.

2) UNFCCC (November 14, 2023), "New Analysis of National Climate Plans: Insufficient Progress Made, COP28 Must Set Stage for Immediate Action", accessed on January 10, 2024.

3) UNFCCC (November 14, 2023), "New Analysis of National Climate Plans: Insufficient Progress Made, COP28 Must Set Stage for Immediate Action", accessed on January 10, 2024.

to reduce emissions is likely to increase. Under these circumstances, there is a need to address demand-side approaches to reduce the burden of introducing "costly" low-carbon technologies for rapid and deep decarbonization.

Recently, a growing body of research has used models to analyze the impacts of emission reduction targets and carbon pricing policies. Recently, the OECD plans to develop an integrated top-down and bottom-up model, including a global CGE model, to assess the economic and other impacts of GHG mitigation via various policy instruments and technologies. These trends indicate the need to develop and update a global CGE to analyze the impacts of various mitigation policies (OECD, 2023, pp.4-10).

Global integrated models are widely used to set pathways to achieve global temperature targets and assess their economic impacts. The results of various global integrated models were used to analyze the economic impacts of short- and long-term mitigation pathways in the IPCC Sixth Assessment Report (IPCC, 2022a, pp.1870-1892).

Moreover, global integrated models continue to be utilized to lay the groundwork for setting global mid- and long-term pathways by considering the 2030 NDC targets and other projections. With the increasing number of countries planning or introducing carbon pricing schemes, the global climate and carbon policy landscape is rapidly shifting. Several countries, including Indonesia, Thailand, and Malaysia, have introduced, or are planning to introduce carbon taxes and/or emission trading systems (World Bank, 2023, pp.iii-viii).4)5)6) Thus, there is an increasing need to analyze the impact of carbon pricing across countries and regions. Global carbon policies, including carbon pricing, have affected the Korean economy. The establishment of an international carbon market and strengthened NDC and carbon neutrality targets are likely to have economic impacts not only on countries that adopt these policy measures but also on other countries and regions.

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4) Joshi and Cortez (March 8, 2023), "Looking Ahead in Malaysia's Carbon-Pricing Journey", accessed on July 18, 2023.

5) Recessary (January 15, 2024), "Thailand Ready for Carbon Tax, Aligning with World Bank's Five Principles", accessed on February 13, 2024.

6) Xiaonan Feng (October 31, 2023), "Indonesia's "Cap-and-Trade-and-Tax" Carbon Pricing Scheme: Only a Light Touch on the Power Market", accessed on November 30, 2023.

In this respect, the global CGE model used in this study can be used as a powerful methodology to analyze the impacts of global policy and environmental issues. Models that cover the entire world and multiple sectors are useful because they can examine the impacts of national and global mitigation policies and the changes in economic activities caused by such policies. They also have the advantage of being able to analyze the economic impacts of changes in one country or region on other countries and regions in an aggregate manner.

Next, there is a great deal of interest in energy system transformation and new and innovative low-carbon technologies, such as DAC, CCUS, and hydrogen, which are technically limited, uncertain, or not economically feasible in many cases. In a context where rapid and deep decarbonization is critical for reflecting the consequences of GST, supply-side options alone are either difficult to achieve or cost-prohibitive. Therefore, demand-side responses have become increasingly important.

Since the IPCC Sixth Assessment Report, research on demand-side approaches has gained greater attention with increasing research collaboration between international organizations and researchers. Research on low-energy-demand scenarios and their impact on achieving the NDC and Net Zero is of increasing importance. Changes in the energy demand side, such as electrification, efficient use of resources, and behavioral changes, can have extensive impacts across key sectors (building, industry, and transport) and accelerate mitigation actions by alleviating the burden of supply-side responses. Demand-side responses are increasingly being acknowledged and emphasized to achieve mitigation targets alongside existing supply-side efforts.

However, despite its importance, research and modeling on the demand-side remain limited. The IPCC Sixth Assessment Report includes demand as an important chapter and demonstrates its high mitigation potential across sectors. (Creutzig et al., 2022b, pp.505-571). The IMP-LD pathway, which emphasizes demand-side responses, represents a reduction in resource consumption through the efficient use of resources and shifts in consumption while maintaining high levels of service and satisfying basic needs (Riahi et al., 2022, pp.309-340). However, there is still a lack of demand-side studies, particularly those with quantitative methodologies, and only limited research and modeling exercises have been conducted to reflect demand-side scenarios. There are limited studies that reflect demand-side changes in different sectors in top-down and bottom-up models, except in the power sector, where demand change is incorporated by changing the scenarios for electricity demand or peak load or applying sensitivity analysis.

Recognizing the importance of energy demand research, major international institutions such as the IIASA and RITE (Japan) have established a research network for global low energy demand scenarios, leading to their development and relevant analysis.7) International research institutes and researchers have led the development of demand-side scenario narratives and their incorporation into top-down and bottom-up models. This research network includes researchers, including IPCC lead authors, building energy demand scenarios and analyzing their impacts using various top-down and bottom-up models.

The Energy Demand Changes Induced by Technological and Social Innovation (EDITS) networks include not only the IIASA and RITE (Japan), but also other institutions and universities, such as AIT (Thailand), LBNL, and RFF-CMCC/EIEE.8) This research network is highly likely to lead the global energy demand research and suggest the directions of the energy demand-related topics in IPCC 7th Assessment Report in the future.

In summary, it is necessary to establish and analyze scenarios with demand-side measures or approaches besides the existing carbon price scenarios to explore the demand-side potential. Therefore, it is necessary to identify trends in global energy demand-related research and analyze the key factors discussed in low energy demand scenarios using a global CGE model.

1.2 Research Objective and Significance

The objective of this study was to understand the trends in low energy demand scenario discussions and model development. This study identified trends in low energy demand scenario narratives, model development discussions, and research keywords. Furthermore, the trends in energy demand analysis and modeling

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7) IIASA (October 24, 2023), “Energy Demand Changes Induced by Technological and Social Innovations (EDITS)”, accessed on June 9, 2023.

8) IIASA (October 24, 2023), “Energy Demand Changes Induced by Technological and Social Innovations (EDITS)”, accessed on June 9, 2023.

exercises in international research institutes, which can be utilized to set research directions and model development plans, were identified.

Moreover, this study developed and updated the global CGE model for energy demand analysis and presented a pilot analysis of a low energy demand scenario. Since the global CGE model, a top-down approach, has limitations in integrating technology development and behavioral changes, it is necessary to identify and incorporate energy demand drivers to improve the global CGE model. This study analyzed the economic impacts of existing mitigation policies, such as carbon pricing, and their impacts under low energy demand scenarios.

Additionally, this study attempted to establish a research network with researchers from international research institutes. Model development and energy demand analysis require a long-term perspective, and research cooperation between different research teams with different ideas and models can bring about synergies in these areas. Therefore, this study investigated the research topics of interest and suggested those that can be utilized for future joint research collaborations. Moreover, the study identified the list of databases and models used by international organizations, specifically the IIASA, for modeling and energy analysis.

Conducting research on energy demand changes using modeling and quantitative methodologies is necessary. There is an increasing need for research that incorporates changes in energy demand into various models. Previous studies have largely focused on the supply-side, such as the deployment of renewable energy technologies; however, the IPCC Sixth Assessment Report emphasized the impact of demand-side changes on energy and GHG emission reductions through behavioral changes and technological developments (IPCC, 2022b, pp.12-34). Also, Korea is experiencing a rapidly-shifting demographic and social structure due to low fertility rates and aging populations. These changes are likely to change energy and service demands.

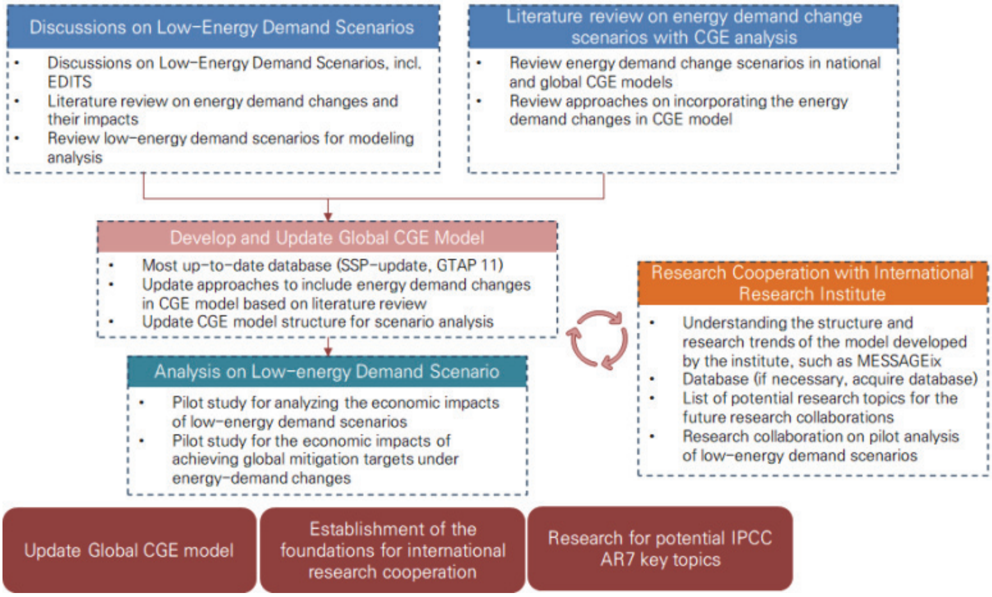
It is also necessary to establish a research network with international research institutes and researchers to participate in global research collaborations on climate change and energy. Research collaboration raises model credibility by networking with leading research groups specializing in top-down and bottom-up models. Understanding other top-down, bottom-up, and integrated models is necessary to improve the global CGE model, and benchmarking certain aspects can be considered, if and where necessary. Moreover, model comparison exercises can increase the credibility and reliability of models. Demand-side research is largely linked to the use of bottom-up models, such as in the building, transport, and power sectors. In the future, it will be necessary to establish a foundation for the development of integrated models. While the global CGE model has limitations in reflecting detailed changes on the demand side and technologies, it can analyze the economic impacts on both sectoral and national economies, which can provide policy implications.

Finally, demand-side scenarios and analyses are likely to be highlighted in preparing the next seventh IPCC Assessment Report and should be considered when designing climate and energy policies. Through research collaboration with researchers in international organizations, it is necessary to strengthen research capacities in modeling and climate-policy analysis as well as to follow global research trends.

1.3 Research Scope

This section outlines the scope and structure of the research. This study analyzed the literature on low energy demand scenarios or analyses with such components and how demand scenarios are incorporated into models. Besides analyzing low energy demand scenarios using CGE models, this study examined how various studies and models with different characteristics analyze low demand scenarios and reflect on components such as energy efficiency improvements and household consumption shifts. These insights can inform the development of the global CGE model. The study also analyzed how industrial and household efforts related to low energy demand contribute to achieving carbon neutrality by 2050. To analyze the period up to 2050, this study used the latest GTAP 11 Power database available as of January 2024 (Aguiar et al., 2023, pp.1-37) and incorporated long-term economic and population projections and carbon pricing scenarios.

Figure 1. Research structure and scope



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 CGE model based on 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

Research Cooperation with International Research Institute

- Understanding the structure and research trends of the model developed by the institute, such as MESSAGEix
- Database (if necessary, acquire database)
- List of potential research topics for the future research collaborations
- Research collaboration on pilot analysis of low-energy demand scenarios

Source: The authors.

2

Research Trends in Energy Demand and Modeling Analysis

As mentioned in the previous section, there is increasing interest in demand-side approaches to energy, but energy demand analyses are lacking, particularly those that employ the CGE model. Various studies have investigated pathways to achieve reductions in energy demand. Low energy demand scenarios typically involve strategies and practices that lead to a significant reduction in energy consumption.

2.1 Literature on Energy Demand and Modeling Analysis

Over the past few decades, energy demand analyses have been conducted utilizing a variety of methodologies. Such analyses include studies on the impacts of temperature changes on energy demand and the impact of price changes on demand for energy sources and on the economy. However, many such studies have been conducted in a qualitative manner—except the relationship between energy prices and consumption—and few works have utilized modeling. This chapter reviews the extant literature on the demand side and identifies some of the models employed therein.

2.1.1 IPCC Sixth Assessment Report (Working Group 3)[9] (IPCC, 2022b; Riahi et al., 2022; Creutzig et al., 2022b)

The IPCC's Sixth Assessment Report WG3 (IPCC, 2022b, pp.12-34) proposed five Illustrative Mitigation Pathways (IMPs). Of these, the IMP-LD scenario focuses on demand reductions through the efficient use of resources, including energy, and shifting consumption patterns. The chapter titled Demand, Service and Social Aspects of Mitigation (Creutzig et al., 2022b, pp.505-571) reviewed the Avoid, Shift,

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9) This section summarizes the Summary for Policymakers, as well as Chapter 3 and Chapter 5 of the IPCC Sixth Assessment Report.

and Improve (ASI) framework in relation to final service demand. The work found that demand-side approaches can reduce the emissions of all sectors in the near- and mid-term, and it emphasized changes in lifestyle as well as technological and market structure innovations. It also emphasized that demand-side approaches have the potential to reduce greenhouse gas emissions by 40-70% in buildings, land transport, and food sectors by 2050 (Creutzig et al., 2022b, pp.505-507). Each component's mitigation potential varies by sector. In addition, the work found that demand-side approaches can achieve significant reductions in greenhouse gas emissions through socio-cultural endeavors, infrastructure planning and use, and the application of end-use technologies by 2050.

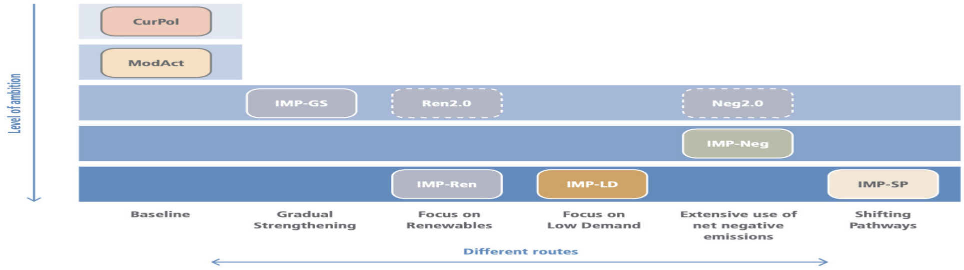
Demand-side approaches stress the achievement of energy demand reductions while providing decent living standards and well-being. Specifically, energy reductions can be achieved by adopting high-efficiency, low-demand pathways (Creutzig et al., 2022b, p.505). The motivation of people and household for changing their behaviors are relatively limited, so it is necessary to touch on psychological aspects in addition to socio-demographic and economic factors. Moreover, the IPCC report's chapter on demand suggests that enhancing social equity can facilitate demand-side approaches to reducing consumption and eventually reduce greenhouse gas emissions (Creutzig et al., 2022b, pp.505-571).

Regarding digitalization and the circular economy, the study pointed to limited evidence of their potential for climate mitigation. It stressed that digitalization can produce gains in efficiency, but increases consumption and thus energy demand at the same time (Creutzig et al., 2022b, p.505). To explore their opportunities, the policy instruments for leading digitalization and circular economy towards climate change mitigation are necessary.

Riahi et al. (2022, pp.309-340) illustrated various mitigation pathways and assessed their fundamental characteristics. The work described the IMP-LD (Low Demand) pathway, one of the five Illustrative Mitigation Pathways (IMPs). This mitigation pathway focuses on low demand and assumes ambitious mitigation actions. This pathway can limit global warming to 1.5 degrees with no or limited overshoot (Riahi et al., 2022, p.311). Compared to the other IMPs, IMP-LD features less reliance on intensive energy supply systems due to lower demand, and the potential to reduce reliance on negative emissions. It is worth noting that this scenario reduces the reliance on Bioenergy with Carbon Capture and Storage (BECCS) to achieve mitigation targets.

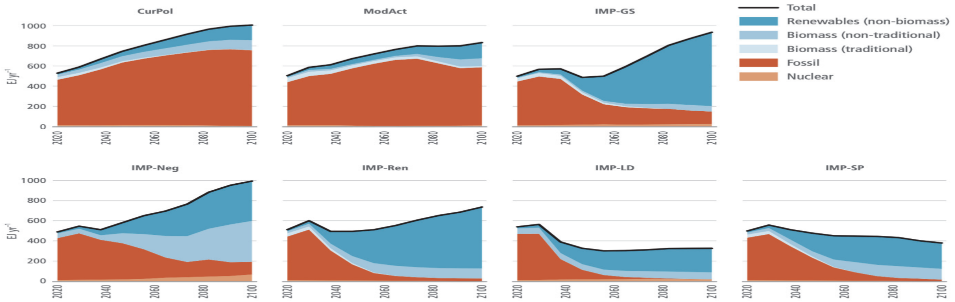
In sum, the chapter highlighted the potential of the Low Demand scenario in climate change mitigation. The IPCC report identifies demand-side approaches as important mitigation strategies, and the importance of those approaches is likely to be further emphasized in the future considering their mitigation potential and reduced burdens in achieving 1.5-degree target with no or limited overshoot.

Figure 2. Illustration of IPCC AR6 Scenarios



Source: Riahi et al. (2022), p.310.

Figure 3. Comparison of energy systems by scenario in IPCC AR6



Source: Riahi et al. (2022), p.312.

2.1.2 Grubler et al. (2018)[10]

Grubler et al. (2018, pp.515-527) established the narrative of low energy demand scenarios and proposed changes to activity levels and energy intensity of the Global North and Global South. It presented an alternative scenario to limit global warming to 1.5 degrees focusing on a future with low energy demand based on current trends. A lower level of energy demand services (LED) resulted in a smaller overall energy system; this downsizing makes it easier to decarbonize the energy supply. In addition, the LED pathway reduces the need for extensive deployment of carbon dioxide (CO_2) removal (CDR) techniques and biofuels. The most commonly modeled negative emissions technology (NET), BECCS, requires significant land use and raises concerns about biodiversity loss. However, these concerns are mitigated in the LED pathways, as they do not rely as heavily on land-intensive solutions.

The study envisioned a comprehensive transformation in energy systems, driven by societal, technological, and policy changes, aimed at achieving sustainable and equitable energy consumption globally. This study proposed a specific low energy demand scenario to meet the 1.5-degree warming climate target without relying on negative emission technologies. It emphasized social and institutional changes in energy service provision and consumption, along with technological innovations. The scenario predicted a significant reduction in global energy demand by 2050, despite demographic and economic growth. This study stands out for its focus on the demand-side of the energy equation, particularly on how changes in energy services can drive a reduction in overall energy demand. It presented an LED scenario, a global vision focused on significant changes in energy consumption and provision.

The LED Scenario proposed by the study features five key factors: quality of life, urbanization, novel energy services, end-user roles, and information innovation. Quality of life emphasizes higher living standards, cleaner environments, and widely accessible services and technologies. Novel energy services capture the trend of demanding newer, more accessible, cleaner, and higher-quality energy services. End-user roles recognize the diversification of roles played by end-users in the energy system, expanding beyond consumption to include producers, traders, citizens, designers, and community members. Information innovation involves

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[10] This section summarizes Grubler et al. (2018).

rapid improvements in information and communication technologies (ICT) that support the application of these drivers.

The distinctive aspects of this scenario are (i) rapid social and institutional changes that focus on how energy services are provided and consumed, alongside technological innovation, (ii) less reliance on stringent climate policy, compared to similar low-emission scenarios, (iii) strong focus on end-use and services that prioritize the end-use and services aspect of energy consumption, and (iv) structural change in upstream sectors as downstream changes in LED induce structural changes in the intermediate and upstream sectors.

The study conducts a comprehensive and detailed analysis to evaluate the quantity and nature of end-use services, including their effects on upstream sectors, offering a granular view of final energy demand from 2020 to 2050. This evaluation is integrated into the MESSAGEix-GLOBIOM integrated assessment modeling framework. Within this framework, the MESSAGE model, focusing on energy supply, is coupled with GLOBIOM, a model dedicated to land use that encompasses agricultural and forestry aspects. Both of these models operate under the IIASA's ix integrated modeling platform, facilitating a comprehensive analysis of how changes in energy demand influence energy supply and land use over a 30-year period.

Three specific constraints were applied: First, it included detailed sector-specific assessments of final energy demand. Second, the range of technological options considered in the model excluded CCS and all forms of negative emission technologies, such as bioenergy with CCS and direct air capture of CO_2. However, the exclusion did not affect afforestation activities, as these are modeled separately by the GLOBIOM model. Lastly, the model was constrained to ensure that cumulative carbon emissions remained within a limit of 390 Gt CO_2 from 2020 to 2100, a limit set to keep global warming to 1.5 degrees by the end of the 21st century.

The key findings of this study are as follows: The LED scenario envisions a future where the sector-wise distribution of energy use remains similar to historical trends, but with significant changes in the technologies and fuels used. By 2050, about 60% of global final energy is expected to be supplied by electricity and hydrogen. The remaining energy will come from a variety of sources, including gases, liquids, and some district heating, while solid fuels such as coal and biomass are almost entirely phased out. This change in energy demand structure leads to more flexibility in supply options, shifting from specific fuel supply chains (from oil to gasoline, for example) to more versatile electricity and hydrogen, sourced from low-carbon options such as solar, wind, biomass, hydro, and nuclear power. The scenario also indicates a gradual reduction in fossil fuel use and excludes the use of CCS for fossil fuels or bioenergy. The LED scenario projects final energy demand in to be about 245 Exajoules (EJ), which is significantly lower than current levels and also below the estimates of similar scenarios discussed in the climate mitigation literature (see Figure 2). This figure is even lower than the lowest scenario reviewed in the IPCC's Fifth Assessment Report, which estimated a final energy demand of 274 EJ by 2050. In the LED scenario, the dramatic transformation of the energy supply sector is facilitated by a substantial decrease in final energy demand. This reduction is achieved through efficiency improvements, shifts in end-use technologies and services, and a widespread move towards electrification. Additionally, the deployment of decentralized, small-scale energy supply technologies, particularly solar photovoltaic energy (PV), plays a key role. This shift leads to a significant expansion of low-carbon energy resources in general, and non-biomass renewables in particular. By 2050, the annual growth rates for low-carbon energy resources and non-biomass renewables are estimated to be around 3% and 5%, respectively. These rates are comparable to or lower than those in other 1.5°C scenarios. However, due to the overall downsizing of the energy system in LED scenarios, these growth rates result in much larger market shares, with low-carbon resources and non-biomass renewables contributing 80% and 55% to the primary energy supply, respectively. The scenario meets the 1.5 degree target and achieves relevant Sustainable Development Goals (SDGs) without relying on negative emissions technologies.

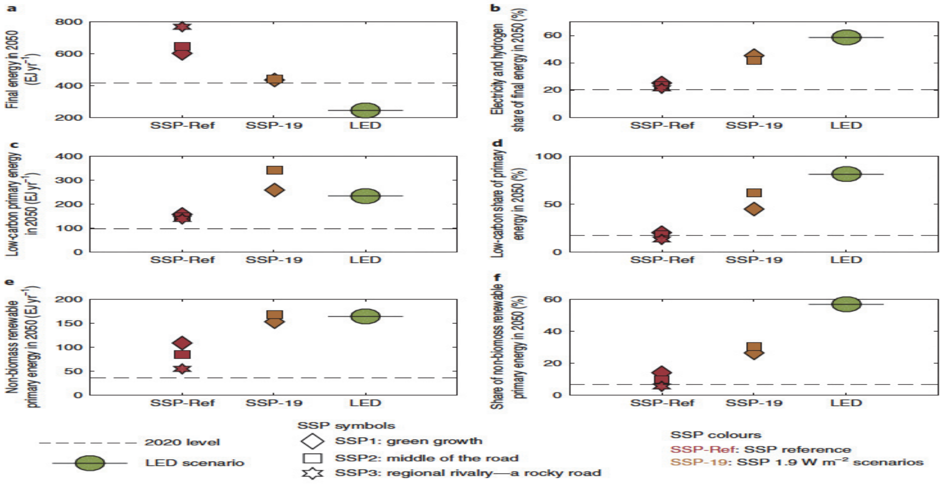
Figure 4. The impacts of Low Energy Demand on 2050 final energy demand

		Region	% change in activity levels (2020-2050)	% change in energy demand (2020-2050)	Activity levels in 2050	Energy demand in 2050 (EJ)	Total energy demand in 2050 (EJ) (GJ capita^{-1})
End-use services	Thermal comfort	North	6	−74	47×10^9 m^2	8	16 (1.8)
		South	63	−79	218×10^9 m^2	8	
	Consumer goods	North	79	−25	67×10^9 units	13	41 (4.5)
		South	175	54	186×10^9 units	28	
	Mobility	North	29	−60	25×10^{12} passenger km	16	27 (3.0)
		South	122	−59	73×10^{12} passenger km	12	
	Contingency reserve						8
Upstream	Public and commercial buildings	North	49	−64	35×10^9 m^2	5	8 (0.9)
		South	77	−82	68×10^9 m^2	3	
	Industry	North	−42	−57	1.0×10^9 t	26	107 (11.7)
		South	−12	−23	5.4×10^9 t	82	
	Freight transport	North	109	−28	31×10^{12} tkm	11	27 (3.0)
		South	75	−12	51×10^{12} tkm	17	
	International aviation and shipping (bunker fuels)						10
Total		North[a]		−53		82	245
		South[a]		−32		153	

All sub-totals and totals are rounded (lower integer at numerical values <0.5, to upper integer ≥0.5). [a]Contingency reserve of 8 EJ is allocated equally to the global North and global South. Bunker fuels are reported at the global level only, consistent with current energy balances and emission accounting frameworks.

Source: Grubler et al. (2018), p.520.

Figure 5. Final energy, low-carbon energy supply, non-biomass renewables under LED Scenarios



Source: Grubler et al. (2018), p.523.

2.1.3 World Economic Forum (2024)[11]

The World Economic Forum (WEF) (2024, pp.4-37) emphasized the importance of transforming energy demand. They estimated that action on energy demand could reduce energy consumption by 31%, or USD 2 trillion per year. The WEF report found that total final energy consumption would increase between 8 and 33% by 2050 from a base year under current policies, while the International Energy Agency (IEA) Net Zero scenario projected a 22% drop between 2022 and 2050 (World Economic Forum, 2024, pp.4-10).

On the energy demand side, the report emphasized the need for current and future efforts to reduce energy intensity. It also highlighted many affordable technologies to reduce energy intensity, and how increasing output while consuming less energy can have a positive effect.

The report also discussed the potential of the buildings, industry, and transportation sectors, which together accounted for 94% of total energy consumption. Through a number of interventions, the Achievable Energy Demand (AED) scenario suggested that energy consumption could be reduced by around 31% compared to a scenario with no efficiency improvements, and by 42% in the Ambition Energy Demand scenario by 2030. The AED scenario also had the potential to reduce energy consumption by about USD 1.1 trillion compared to 2022 demand, exhibiting the significant economic potential.

The WEF white paper also (2024, pp.13-37) identified three types of energy demand levers: energy savings, energy efficiency, and value chain collaboration. Energy saving refers to the reduction of energy consumption through changes in corporate behavior and activities, and may include AI-driven software, HVAC energy intensity, and so on. Energy saving is considered to be the easiest lever to operate, with the shortest payback period. The next lever is energy efficiency, which includes retrofits of buildings, reduced energy requirements for operations, and so on. Finally, value chain collaboration is considered the most complex and has the longest payback period. It includes demand substitution and demand response to reduce the energy intensity of city heating.

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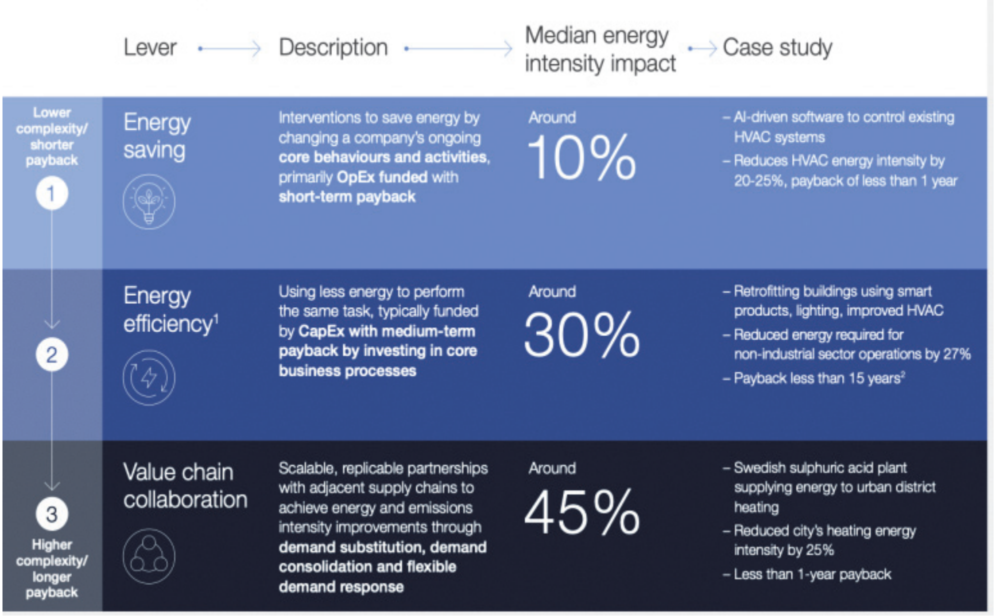
11) This section summarizes the World Economic Forum (2024), pp.4-37.

Figure 6. Energy demand levers



	Lever	Description	Median energy intensity impact	Case study
Lower complexity/ shorter payback 1	Energy saving	Interventions to save energy by changing a company's ongoing **core behaviours and activities,** primarily **OpEx funded** with **short-term payback**	Around 10%	- AI-driven software to control existing HVAC systems - Reduces HVAC energy intensity by 20-25%, payback of less than 1 year
2	Energy efficiency[1]	Using less energy to perform the same task, typically funded by **CapEx with medium-term payback by investing in core business processes**	Around 30%	- Retrofitting buildings using smart products, lighting, improved HVAC - Reduced energy required for non-industrial sector operations by 27% - Payback less than 15 years[2]
3 Higher complexity/ longer payback	Value chain collaboration	Scalable, replicable partnerships with adjacent supply chains to achieve energy and emissions intensity improvements through **demand substitution, demand consolidation and flexible demand response**	Around 45%	- Swedish sulphuric acid plant supplying energy to urban district heating - Reduced city's heating energy intensity by 25% - Less than 1-year payback

Source: WEF (2024), p.11.

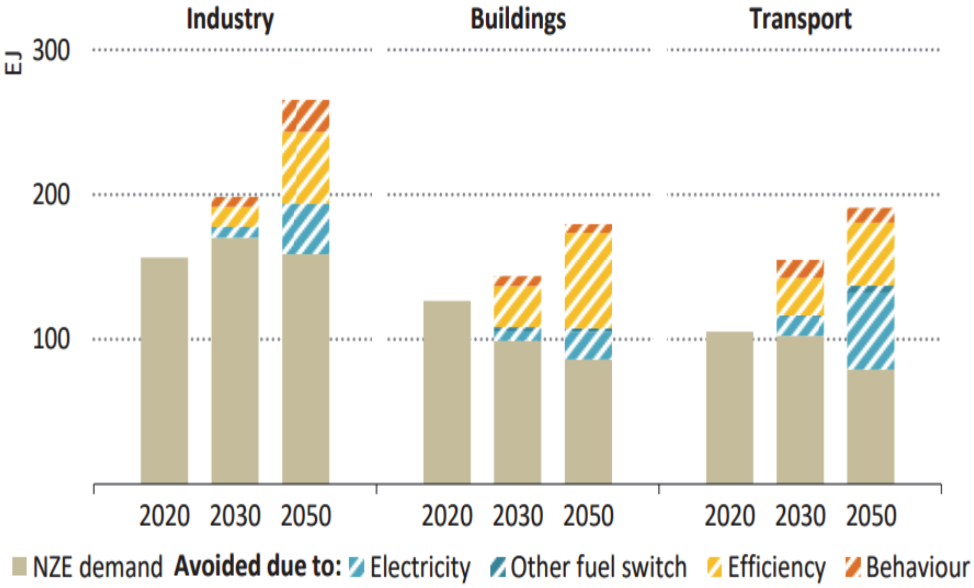
However, the report pointed to a lack of policy support for such measures, and identified several key limitations, such as low awareness of the potential of demand-side response, and insufficient returns from measures that can lower demand.

The study provided examples of energy demand or energy intensity reductions in industry. For example, in the chemicals sector, which accounted for about 10% of global energy demand, energy intensity has been reduced by switching to non-steam catalytic methods for steam cracking, which is an energy-intensive process. Examples of value chain collaboration include increasing the use of scrap metal in electric arc furnaces (EAF) in the steel sector and increasing steel production utilizing direct reduced iron-electric arc furnaces (DRI-EAF).

2.1.4 IEA (2021)[12]

The IEA (2021) stressed energy efficiency as the most important policy measure for diminishing energy demand and attaining carbon neutrality. The IEA's 2050 Net Zero scenario incorporates over 40 energy efficiency measures, affirming that decreasing energy demand through efficiency improvements, electrification, and behavioral changes will lead to achieving climate goals.

Figure 7. The role of energy efficiency by sector in the 2050 Net Zero Scenario



Source: IEA (2021), p.65.

2.1.5 Laborde et al. (2021, pp.375-390)[13]

Laborde et al. (2021, pp.375-390) analyzed the socio-economic impacts of COVID-19 using a global CGE model. The analysis applied IFPRI's global CGE and POVANA models to conduct a household-level analysis of the socio-economic impacts of

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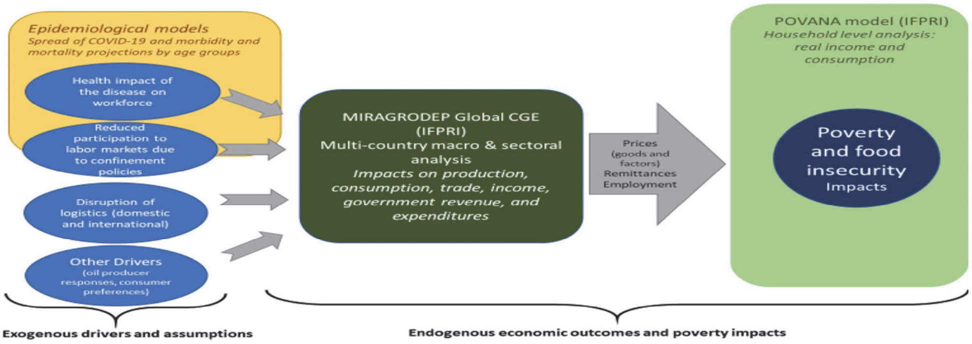
[12] This section summarizes the IEA (2021), pp.47-94.

[13] This section summarizes Laborde et al. (2021), pp.375-390.

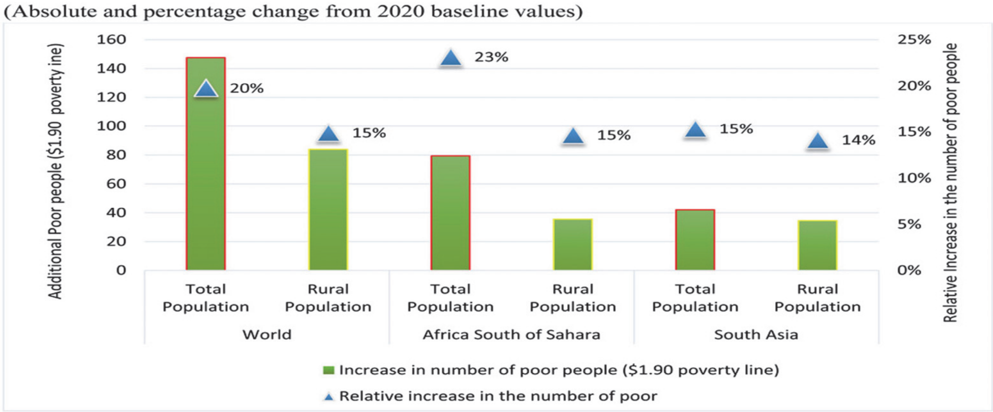
COVID-19 on labor, income, demand, participation in the labor market, and logistics. The global CGE model was used to analyze macroeconomic impacts on production, consumption, trade, income, as well as government revenue and expenditure. It also provided fed price, remittance and employment information to the POVANA household model. While this study focused on COVID-19, the approaches and assumptions of demand-side shocks could be considered in the development of low energy demand scenarios.

Figure 8. Modeling structure



Source: Laborde et al. (2021), p.379.

Figure 9. Impacts of COVID-19 based on CGE analysis



Source: Laborde et al. (2021), p.383.

2.1.6 Zhang et al. (2022)[14]

Zhang et al. (2022, pp.5614-5640) analyzed the economic and environmental impacts of ICT utilization in Japan. The AIM/CGE (Japan) model was applied and the IO coefficient was adjusted to reflect reduced intermediate and labor demand when ICT technologies are adopted in production and end-use sectors. The AIM/CGE model was built using 2005 Input-Output Table in Japan. This study utilized the model to analyze the impacts of the increased utilization rate of ICT services in six industries (finance, public services, manufacturing, distribution, services and medical care, agriculture, and infrastructure).

The study indicated that the usage of ICT services can increase production efficiency, which reduces the intermediate inputs per unit of output. The study identified 36 ICT services in six sectors and categorized them into two groups. Group 1 consisted of mature services with relatively high levels of ICT utilization, such as remote work and online shopping. Group 2 comprised relatively new ICT services, such as AI and the Internet of Things (IoT).

The study considered an increase in electricity consumption by ICT equipment. Based on the historical data, the study investigated trends in electricity consumption by ICT equipment use and forecast consumption up to 2030. The study estimated that the electricity consumption by ICT equipment would reach 120 to 150 percent of 2020 levels by 2030.

This study established a baseline scenario and an ICT accelerated scenario. The accelerated scenario considered accelerated usage of ICT technologies. For this scenario, the study identified four cases, which indicate the non-ICT sectors' demands on ICT services. The study showed how ICT utilization could increase electricity demand in the ICT sector but lead to greater energy demand reductions in other sectors. ICT services can save on labor and improve the coordination of supply and demand, which can improve production efficiency.

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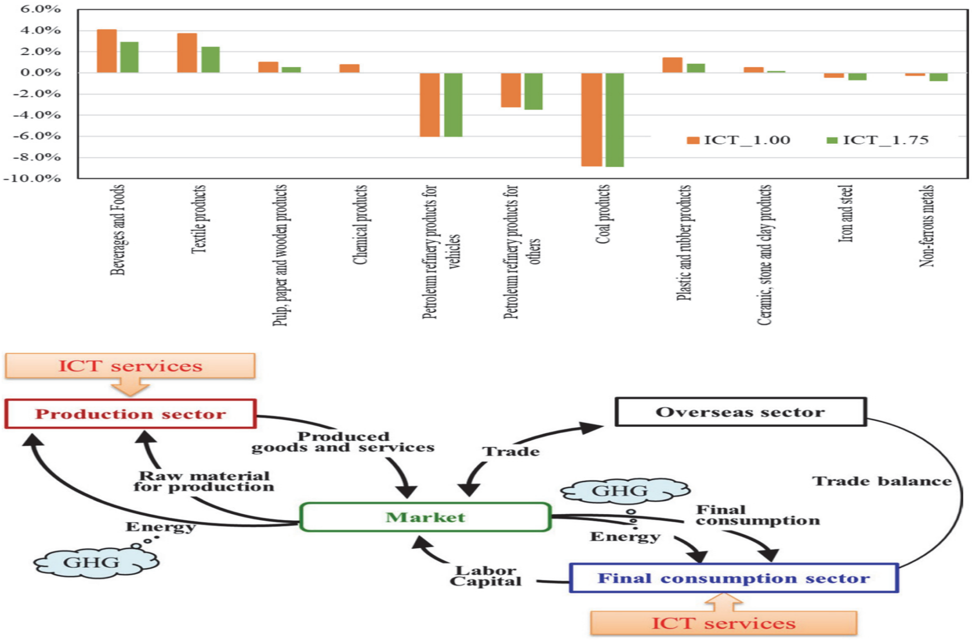
14) This section summarizes Zhang et al. (2022), pp.5614-5640.

Figure 10. The role of ICT services in production and energy consumption sectors



Source: Zhang et al., (2022), p.5627 (upper figure), p.5617 (lower figure).

Zhang et al. (2022) showed that ICT acceleration could further reduce greenhouse gas emissions relative to the baseline by 2030 in Japan. In addition, ICT utilization could significantly reduce fossil fuel consumption thanks to efficiency improvements in logistics and energy saving. The study emphasized the potential of ICT utilization in greenhouse gas emission reductions while increasing GDP growth.

2.1.7 Sethi et al. (2020)[15]

Sethi et al. (2020) conducted a systematic analysis on urban climate change mitigation, addressing the mapping of urban mitigation measures and combinations of measures, determining GHG abatement potential, studying ex-post policy analysis, and ascertaining research trends. This study found a number of demand-side mitigation

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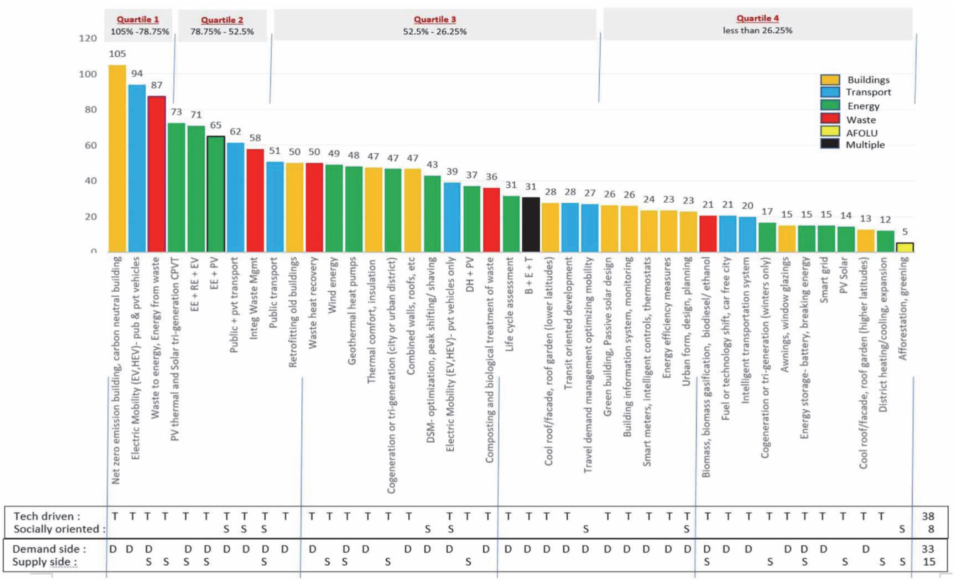
[15] This section summarizes Sethi et al. (2020).

measures in urban mitigation with significant mitigation potential. The work stressed the importance of diverse demand-side approaches to urban mitigation, and provides some insight into sustainable urbanization in line with SDGs, describing the necessity of incorporating disciplinary knowledge for better utilization of data and information, embracing innovative technologies, realizing mitigation potential in cross-sectoral policy design, and emphasizing the importance of soft infrastructure that shapes human behaviors.

Figure 11. Average GHG abatement potential from BAU (%)



Source: Sethi et al. (2020).

2.1.8 Huang et al. (2023)[16]

Huang et al. (2023) conducted a systematic review of the rebound effects of energy efficiency improvements, focusing on the CGE analysis approach. The work found that energy efficiency improvements could reduce energy consumption, but at the same time, rebound effects could offset these reductions or even exceed them.

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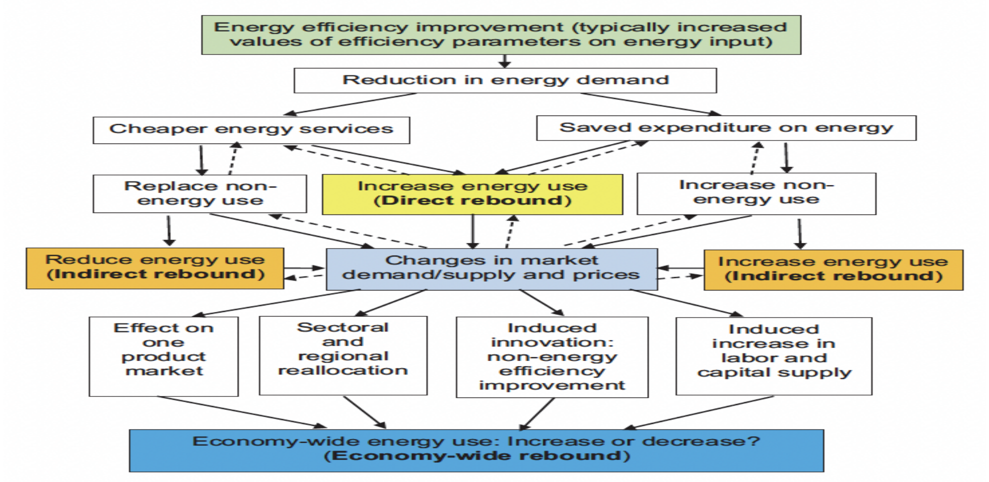
[16] This section summarizes Huang et al. (2023).

Rebound effects can be either direct or indirect. For example, energy efficiency gains can lower the price of energy services, supporting more consumption of those services, thereby leading to more energy use. This would be considered a direct rebound effect. On the other hand, energy efficiency improvements can reduce the energy costs incurred by an agent, who could then enjoy other activities thanks to the savings from the lowered energy costs. This additional energy consumption of additional activities can be considered as an indirect rebound effect. The study explored cases of increased energy efficiency as part of its analysis. It considered (1) exogenous energy efficiency improvements that change energy-augmented efficiency parameters, (2) energy efficiency improvements with other measures, such as fossil fuel subsidies and improvements to the efficiency of capital and labor in production, and (3) energy efficiency improvements resulting from other measures. In general, exogenously-set energy efficiency improvements have led to some positive rebound effects, and relatively few studies indicated rebound effects exceeding 100%. Huang et al. (2023) found that almost all CGE analyses assumed costless energy efficiency improvements. When other measures increase the costs of using energy, some studies found a negative rebound effect, which could further reduce energy use. For instance, taxes on energy sources can lead to negative rebound effects. However, energy efficiency improvements resulting from other policy measures, such as fuel efficiency standards, led to positive rebound effects. This study broadly reviewed the energy efficiency-related studies utilizing CGE analysis to understand these rebound effects.

Figure 12. Structure of economy-wide rebound effects in the CGE model



Source: Huang et al. (2023), p.3.

2.1.9 Gaur et al. (2022)[17]

According to Gaur et al. (2022), existing studies on LED scenarios see that demand reduction is accomplished through four main strategies, which include the use of technology, changes to economic systems, behavioral and lifestyle changes, and policy interventions with specific options and impacts affecting end-use sectors (see Figure 13). In LED scenarios, these strategies would be implemented and widely adopted, leading to a significant reduction in overall energy consumption while still meeting the needs of the population.

This study described the Irish Low Energy Demand (ILED) approach, implemented in the TIMES-Ireland Model (TIM), which illustrates a unique scenario for reducing energy service demand (ESDs) without hampering economic growth. It is achieved through various strategies and measures, such as altering travel patterns, enhancing efficiency in energy usage, concentrating on urban development, focusing on less energy-intensive economic activities, and modifying social infrastructure. In contrast to a BAU growth model, the Irish LED scenario facilitates meeting ambitious

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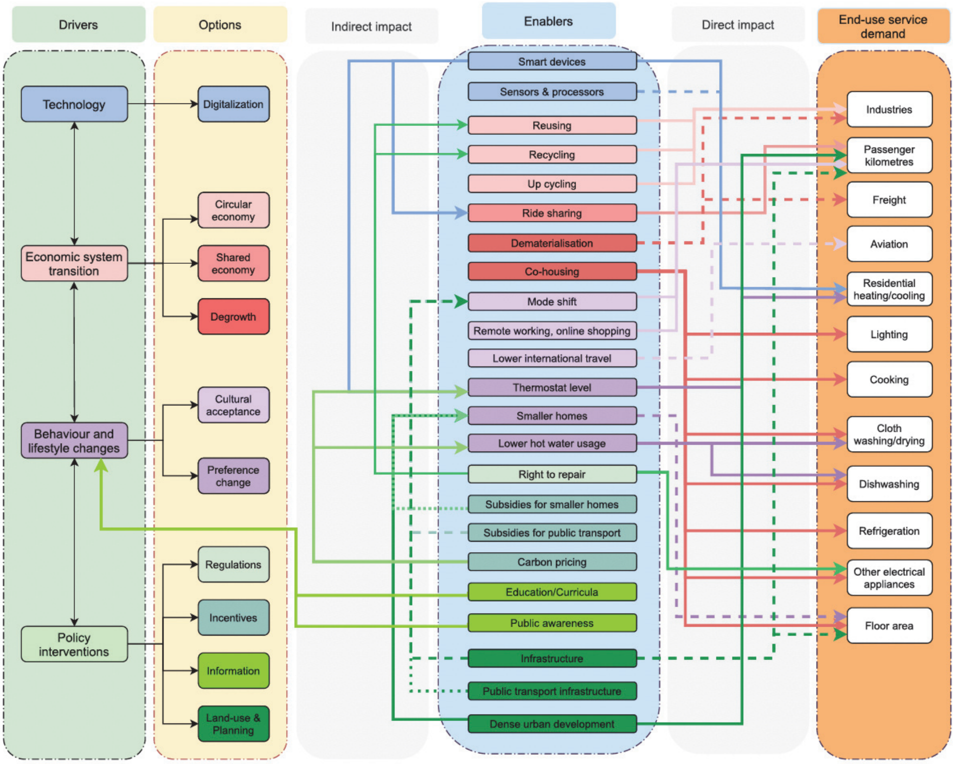
[17] This section summarizes Gaur et al. (2022).

decarbonization goals with a more gradual overhaul of the energy system. This results in reduced capital investment and marginal abatement costs, and less dependence on new technologies.

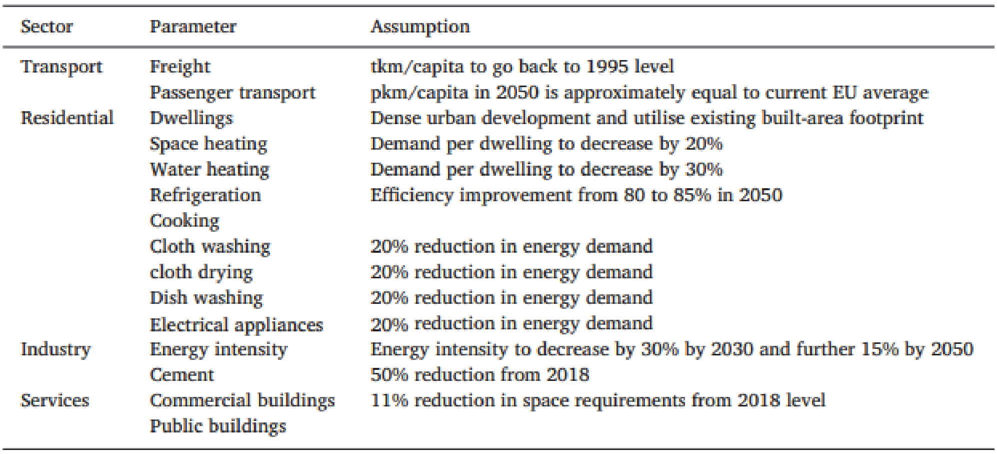
Figure 13. Drivers of energy demand reductions and their impacts



Source: Gaur et al. (2022), p.4.

The Irish Low Energy Demand (ILED) scenario illustrates how altering ESD can aid in achieving ambitious decarbonization goals. It involves densifying urban settlements, significantly investing in public transport, and enhancing walking and cycling infrastructure. It also involves de-materializing the economy to facilitate major shifts in transport modalities, reduce building heating needs, and lower demand for materials such as cement. The study compares a BAU energy demand scenario with ILED across various climate mitigation targets, including both immediate ambitious goals and a net-zero target for 2050. ILED primarily focuses on 'avoid' and 'shift' approaches to reduce ESD, adding these options to the more commonly modeled 'improve' category in energy demand scenarios.

Figure 14. Assumptions in energy service demand



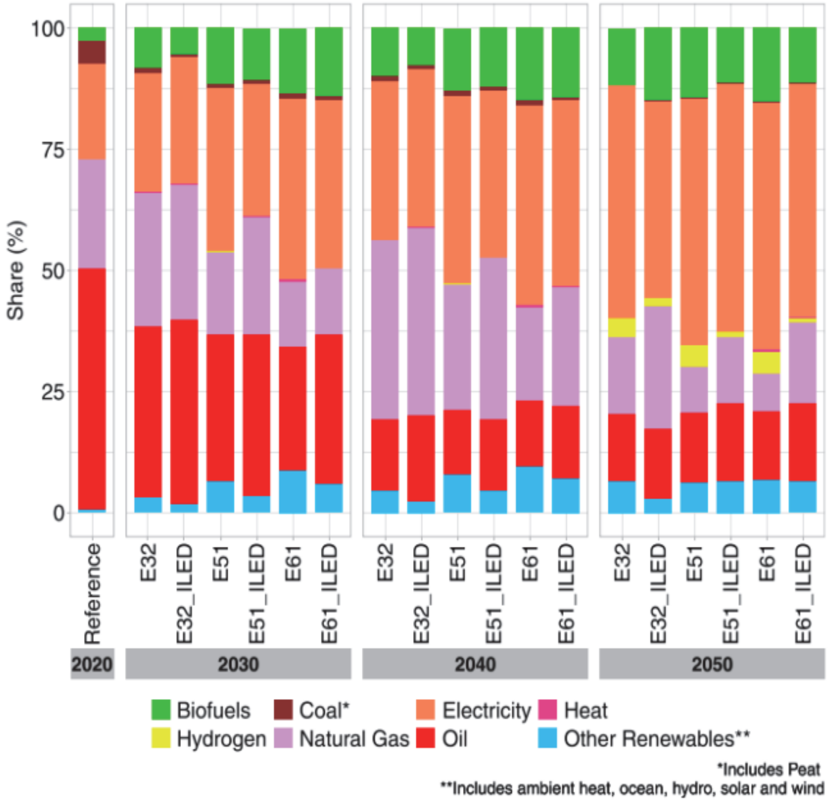
Sector	Parameter	Assumption
Transport	Freight	tkm/capita to go back to 1995 level
	Passenger transport	pkm/capita in 2050 is approximately equal to current EU average
Residential	Dwellings	Dense urban development and utilise existing built-area footprint
	Space heating	Demand per dwelling to decrease by 20%
	Water heating	Demand per dwelling to decrease by 30%
	Refrigeration	Efficiency improvement from 80 to 85% in 2050
	Cooking	
	Cloth washing	20% reduction in energy demand
	cloth drying	20% reduction in energy demand
	Dish washing	20% reduction in energy demand
	Electrical appliances	20% reduction in energy demand
Industry	Energy intensity	Energy intensity to decrease by 30% by 2030 and further 15% by 2050
	Cement	50% reduction from 2018
Services	Commercial buildings	11% reduction in space requirements from 2018 level
	Public buildings	

Source: Gaur et al. (2022), p.9.

Three mitigation pathways are explored, each with two different energy system demand scenarios: BAU and ILED. The pathways are named based on the percentage reduction in CO_2 emissions from the energy system by 2030, relative to 2018 levels. The first pathway, the E51 pathway, aims for a 51% reduction in energy-system CO_2 emissions from 2018 to 2030 and achieves net zero emissions by 2050. It aligns with the national climate target of cutting economy-wide emissions by 51% and requires the agriculture sector to reduce emissions by 51%. The next pathway, E61, is similar to E51, but targets a 61% reduction in energy-system CO_2 emissions between 2018 and 2030 and also reaches net zero by 2050. Under this pathway, the agriculture sector is expected to achieve a 33% reduction in emissions. Lastly, the E32 pathway does not meet the national mitigation target, but does align with the Climate Action Plan 2019. It sets a goal to reduce non-ETS GHG emissions by 30% in 2030 (relative to 2005) and by 80% in 2050 (relative to 1990).

The size of the energy system, which encompasses both the supply side and the infrastructure required to deliver energy, is directly influenced by final energy demand. In scenarios where ESD follows a BAU projection, the energy system is larger compared to that in the ILED pathway. Consequently, scenarios with a BAU ESD projection require significantly higher investments. The E61 scenario, in particular, demands the highest level of investment. This is because the energy system in the E61 scenario requires additional efforts to meet the ambitious targets set by the climate bill, necessitating greater financial resources for implementation.

Figure 15. Fuel mix changes by scenario



Source: Gaur et al. (2022), p.14.

2.1.10 Kuhnhenn et al. (2020)[18]

Kuhnhenn et al. (2020) proposes a Socio-Technical Scenario (STS) by envisioning a socio-economic transition that serves as the basis for scenario assumptions. These assumptions involve reducing consumption and production in energy-intensive sectors, creating space for less energy-intensive sectors to thrive. This transformation goes beyond mere reductions; it aims for a democratically controlled structural shift that promotes social, economic, and ecological justice, and improved well-being for everyone. The scenario‘s parameters deliberately focus on consumption reductions that do not compromise basic material needs while enhancing the fulfillment of non-material needs.

To assess the impacts of the STS, a simulation tool called the Global Calculator (GC) is employed, which is aligned with the STS's similar goals. The GC is a model of the world's energy, land, and food systems running up to the year 2050. It is underpinned by a vast array of data sources, including scientific literature, government reports, and industry data. It includes assumptions about technological advancements, economic trends, and behavioral changes that may occur over the period up to 2050. The model generates a pathway that shows how these changes could impact global emissions, temperature rise, and energy consumption. The core of the model's output is the projection of greenhouse gas emissions and their impact on global temperatures. It uses climate models to estimate how different emissions scenarios could affect global warming.

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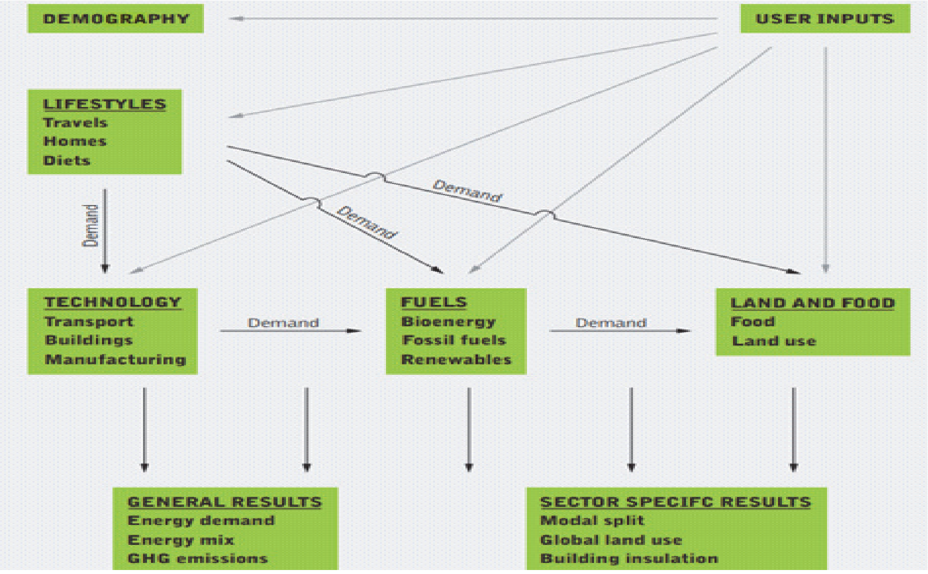
[18] This section summarizes Kuhnhenn et al. (2020).

Figure 16. Structure of global calculator



Source: Kuhnhenn et al. (2020), p.24.

The study established different assumptions for Annex I and non-Annex I countries. For Annex I countries, from 2020 to 2030, they reduce road-based passenger transport per person to 1990 levels, with a 17% reduction, followed by a 20% reduction until 2050. This reduction primarily targets urban areas, which account for 70% of the total reduction. Rural areas contribute the remaining 30%. The study assumes a shift from cars to walking, biking, buses, and trains, especially in urban areas, where the share of car transport is assumed to drop from 64% in 2015 to 12% in 2050. By 2040, urban modal splits should align with the best 50 European cities. Car ownership disincentives, expensive parking, and car-sharing will encourage this transition. Car occupancy is projected to increase from 1.6 to 2.5 people per car in both urban and rural areas. Additionally, a 20% increase in passengers for buses and trains is expected, raising public transit ridership. For non-Annex I countries, in the context of road-based passenger transport, the assumption is a gradual convergence to the levels seen in Annex I countries by 2050, both in urban and rural areas. This convergence implies an increase from 4,190 passenger kilometers per person annually to 7,526 in urban areas and from 1,867 passenger kilometers per person to a remarkably high 23,878 in rural areas. Concerning car transport, the study anticipates a 17% reduction in urban areas but a substantial 67% increase in rural regions. Car occupancy is expected to remain stable from 2015 onward, with a projected car occupancy of 1.9 passengers per car in urban areas and 2.2 passengers per car in rural areas by 2050. For buses, the study assumes an average occupancy of 32 passengers per bus in 2050, while trains are expected to have an average occupancy of 461 passengers per train in the same year.

Based on these assumptions, in the LED scenario, final energy demand is higher for Annex I countries in 2030 and 2050, and lower for Non-Annex I countries in 2030 and almost the same in 2050. This difference is expected because the STS assumes lower energy demand in the Global North (Annex I) that enables self-determined development in the Global South (Non-Annex I). Regarding the energy mix, the STS and LED scenarios differ here. In 2030, the STS has a slightly lower total global final energy demand, but higher primary energy production, indicating a more efficient energy mix. However, by 2050, the STS has much lower final energy demand and a more efficient primary energy supply. Cumulative CO_2 emissions from 2020 to 2100 are higher in the LED scenario, mainly due to greater carbon sequestration in the STS. Despite differences in energy approaches, the emission pathways are notably similar.

2.1.11 Barrett et al. (2022)[19]

Barrett et al. (2022, pp.726-735) proposes a comprehensive approach to analyzing energy demand reduction, integrating a variety of strategies and perspectives to provide a thorough understanding of the contribution of energy demand reductions to meeting climate goals. The proposed modeling framework focuses on national-level analysis to better understand and quantify the role of energy demand reduction in achieving climate targets. Key aspects of this framework include assessing energy demand reductions, broadening energy efficiency approaches, and providing whole-economy and sectoral perspectives.

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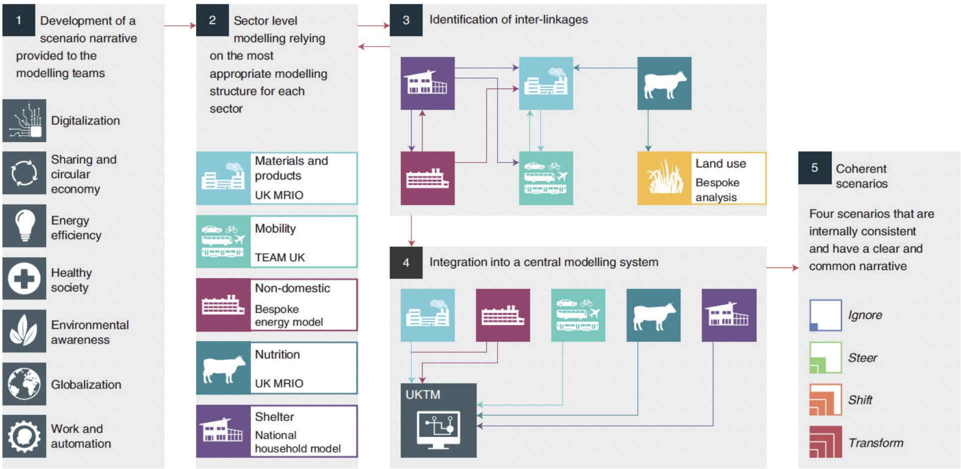
19) This section summarizes Barrett et al. (2022), pp.726-735.

The approach for developing energy scenarios begins with creating a narrative based on key trends affecting energy demand. This narrative guides the detailed, sector-specific modeling of energy demand. A critical aspect of this process is mapping the interdependencies between sectors to ensure a cohesive overall scenario. This leads to integrating these individual analyses into a holistic framework, focusing on the implications of lower energy demand on the energy supply system and the role of Carbon Dioxide Removal (CDR) technologies. The culmination of this process is the formulation of four distinct scenarios: Ignore, Steer, Shift, and Transform, each representing different potential energy futures.

Figure 17. Framework for analyzing Low Energy Demand scenarios



Source: Barrett et al. (2022), p.727.

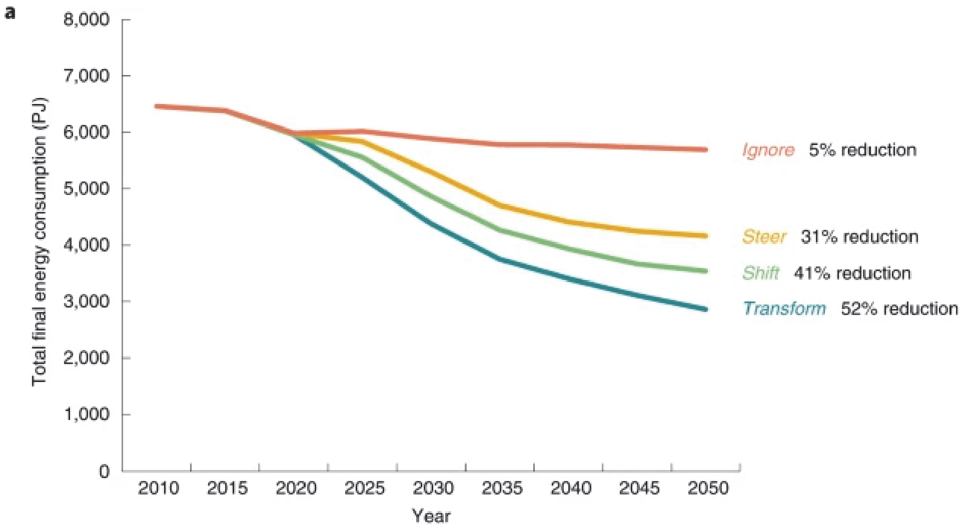
Table 1. Four different scenarios

Scenario	Description
Ignore	Identifies levels of energy demand up to 2050 assuming only existing UK government climate policy instruments are implemented (as of 2018). This includes existing policy for delivery of emission reductions but not climate targets or ambitions.
Steer	Adopts the more ambitious legislated target of net-zero GHG emissions by 2050 but falls just short of meeting it. Uses the same energy service-demand projections as the Ignore scenario but implements a wide range of energy efficiency options.
Shift	Similarly to Steer, adopts the net-zero GHG emissions target. Significant shift in the attention given to energy demand strategies, providing an ambitious program of interventions across the whole economy describing what could possibly be achieved with currently available technologies under current social and political framings.
Transform	Similarly to Shift, this scenario adopts the net-zero GHG emissions target. Considers transformative change in technologies, social practices, infrastructure and institutions to deliver both reductions in energy as well as numerous co-benefits such as health, improved local environments, improved work practices, reduced investment needs and lower cumulative GHG emissions.

Source: Barrett et al. (2022), p.728.

The study highlights that energy demand reduction can go beyond traditional energy efficiency measures. This broader approach can lead to significantly greater reductions in energy demand across all sectors. By implementing comprehensive demand reduction strategies, the study finds a notable decrease in the need for large-scale engineered CDR options such as BECCS or direct air capture. A reduction in energy demand can significantly cut down the investment needed across the energy system. This implies cost savings and potentially more efficient allocation of resources. Furthermore, the approach provides earlier opportunities for mitigating climate change and results in a greater reduction in cumulative emissions, enabling the pursuit of more ambitious climate targets. In the specific context of the United Kingdom, the most ambitious energy demand scenario, called Transform, is shown to achieve a 52% reduction in final energy consumption by 2050 compared to 2020 levels. This is in contrast to the Steer scenario, which relies solely on energy efficiency measures and achieves a 31% reduction. The Transform scenario effectively meets the UK’s net-zero target, whereas the Steer scenario falls short. The difference between these scenarios underscores the importance of not just improving efficiency but also shifting and avoiding energy demand to achieve significant reductions in energy use. The insights from this analysis highlight the multi-faceted approach required to meet ambitious climate goals, emphasizing the role of energy demand management alongside technological solutions.

Figure 18. Final energy demand changes by scenario



Source: Barrett et al. (2022), p.729.

2.1.12 Semieniuk et al. (2021)[20]

Semieniuk et al. (2021, pp.313-318) points out the difficulty of reducing energy demand while ensuring continued economic growth in IPCC scenarios that limit global warming to 1.5°C. IPCC scenarios heavily depend on significant improvements in energy efficiency to meet development needs. Many propose unusual patterns of robust economic growth coupled with steep reductions in energy consumption, challenging the traditional correlation between energy use and development. The study suggests that a more feasible approach may be to focus on rapid decarbonization

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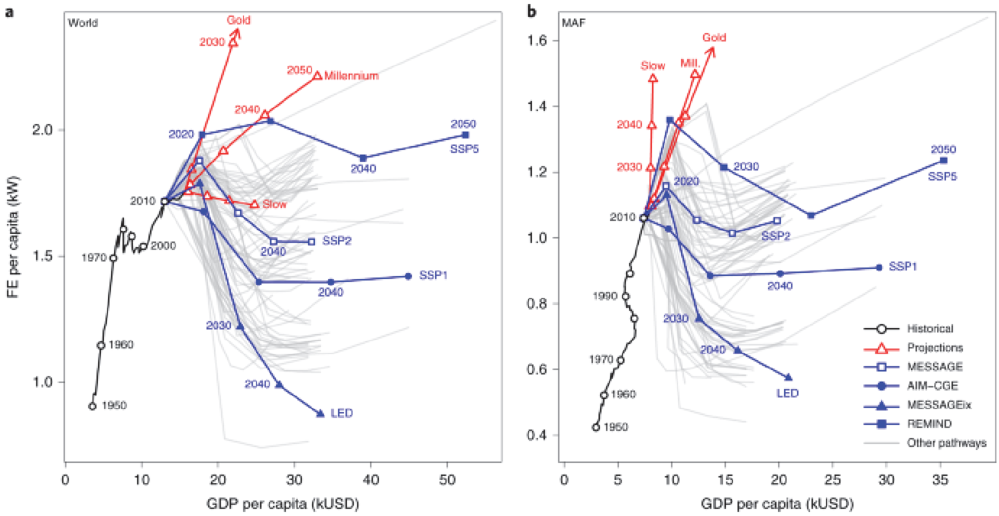
[20] This section summarizes Semieniuk et al. (2021), pp.313-318.

of the energy supply rather than solely on limiting energy demand. It also highlights the need for incorporating insights from development economics and other disciplines to create realistic and sustainable energy and economic policies. This approach is crucial for addressing the interconnected challenges of energy policy, economic development, and climate change. The paper advocates for quickly exploring energy supply decarbonization as an alternative or complementary strategy to demand reduction, especially in the context of developing regions.

The study highlights that the assumptions made in IPCC scenarios about decoupling, economic catch-up, and energy demand in regions such as the Middle East and Africa (MAF) are not consistent with historical data and insights from development economics. For instance, these scenarios often project a decline in per capita final energy (FE) demand to levels below what is considered necessary for a decent standard of living, even as income growth accelerates. This implies that these regions would have a similar mitigation capacity as developed countries, which contradicts their current development paths.

Stringent mitigation policies, as outlined in the IPCC special report, aim to deviate from historical trends linking energy consumption with economic growth. The report calculates that to achieve the 1.5°C target, a significant shift from the traditional energy-income relationship is necessary within the next two decades. This shift is depicted in Figure 19, which contrasts future GDP projections and per capita final energy (FE) consumption with past data. Historically, the trend shows economic growth running parallel with increased energy demand, with faster economic growth periods correlating with even higher energy demand. However, in stark contrast, the scenario pathways in the IPCC report envision robust GDP growth per capita coupled with a sustained and unprecedented reduction in per capita FE, particularly in the 2020s and 2030s. Similar patterns are observed for primary energy (PE) and in scenarios limiting warming to 2°C. Essentially, these pathways propose a novel trajectory where economic growth is decoupled from increased energy consumption, marking a significant shift from historical patterns.

Figure 19. Output and final energy per capita until 2050 (world and MAF region)



Source: Semieniuk et al. (2021), p.316.

The structural shift described in the context of global energy and economic trends is particularly noticeable at the regional level, especially in areas with lower labor productivity, such as the MAF region. This region exhibits a notable change in its economic and energy dynamics. From 1973 to 2000, the MAF region experienced very slow GDP per capita growth (0.1% annually) and modest growth from 2000 to 2018 (1.4% annually). However, projections for 2020 to 2050 show a much healthier annual growth rate of 2.5% in GDP per capita.

Despite this positive economic growth forecast, energy consumption trends in the MAF region deviate from historical patterns. Since 1950, final energy (FE) per capita in this region has consistently risen, reaching around 1 kW per capita, still below the global average of 1.75 kW per capita. This average masks significant variation between Middle Eastern oil exporters and sub-Saharan agrarian economies. While expectations point to energy consumption converging toward the global average, especially given the strong correlation between development and energy consumption, the scenarios project substantial declines in final energy demand for the MAF region.

The authors suggest incorporating insights from development economics and other disciplines to generate more plausible assumptions regarding energy demand patterns, particularly in the context of financial, investment, and stability issues in energy transitions.

2.1.13 Oshiro et al. (2021)21)

Japan has submitted its Nationally Determined Contribution (NDC) to the UNFCCC and has announced a Mid-Century Strategy (MCS), with the objectives of decreasing greenhouse gas emissions by 26% compared to 2013 levels by the year 2030 and achieving an 80% reduction by 2050. Oshiro et al. (2021) propose a LED scenario for Japan ('LoDem' scenario). The scenario focuses on reducing ESD through various measures. These include dematerialization, improvements to material efficiency, reduced hot water usage, lower thermostat levels, a shift to non-motorized and public transportation, decreased passenger trip frequency, and lower freight demand. Implementing these demand reduction strategies alongside energy-efficient technologies could decrease Japan's final energy demand by up to 37% by 2050. Additionally, these measures are expected to cut dependency on CCS measures by half by 2050. A sectoral analysis reveals that the industrial sector must play the biggest role in decreasing system costs through demand reduction, followed by the building and transport sectors.

The study further aims to identify the primary challenges and prospects confronting Japan concerning its MCS. The assessment also took into account the effectiveness of initiatives aimed at reducing ESD. To do so, the work constructed a model for estimating ESD, taking socio-economic factors into consideration. It also developed a method to quantify the effects of measures intended to lower ESD. Ultimately, it evaluated the efficacy of these demand reduction measures in Japan for achieving the MCS, utilizing an energy system model.

Two models are deployed to evaluate how energy demand reduction measures influence the transformation of Japan's energy system. Alongside the partial equilibrium energy system model, termed AIM/End-use[Japan], where ESD is treated as an externally fixed parameter, the study employs an ESD model. This

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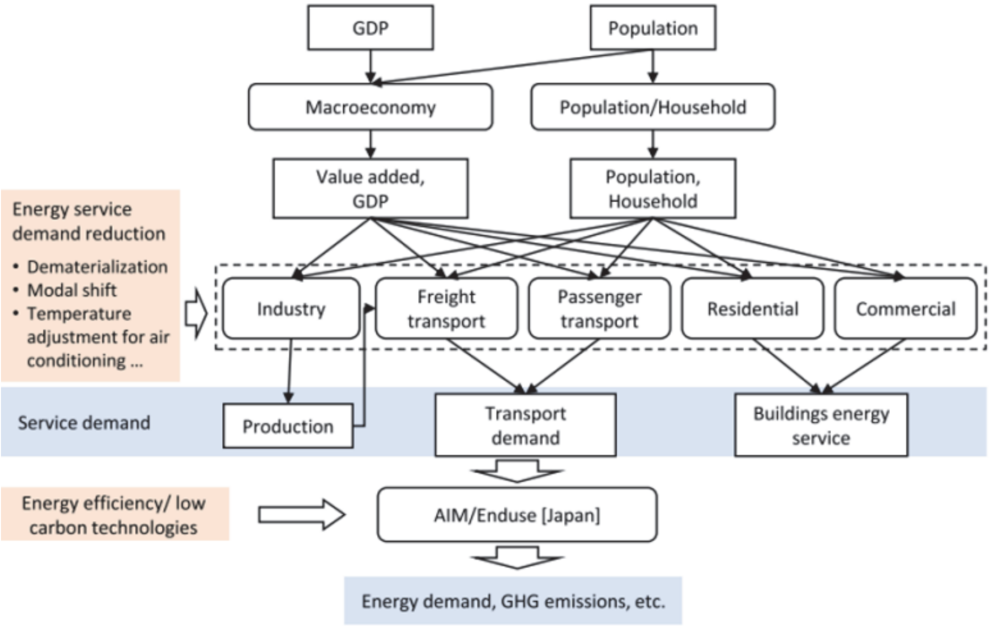
21) This section summarizes Oshiro et al. (2021).

model calculates service demand in the energy sector taking into account socio-economic indicators. While historical trends primarily guided the estimation of energy service demand, the energy system model has the advantage of explicitly considering dynamic technological advancements to meet decarbonization objectives.

Figure 20. Research framework and model structure



Source: Oshiro et al. (2022), p.3.

This study explored ESD scenarios in Japan. The first scenario, called the Default Demand (DefDem), represented the baseline situation, and featured no specific ESD reduction measures. ESD for 2050 were estimated using a model based on population and GDP growth based on the Shared Socioeconomic Pathways (SSP2) framework.

The second scenario, Low Demand (LoDem), incorporated various ESD reduction measures, including improvements to material efficiency and behavioral changes. Additionally, the study introduced separate scenarios (LoInd, LoBui, and LoTra) to assess the impact of ESD reductions in the industrial, building, and transport. sectors. Assumptions in the LoDem are listed in below table.

Table 2. Assumptions in the Low Demand scenario

Sector	Measure	Description
Industry	Dematerialization	- Industrial production reductions based on dematerialization - Factors: 0.9 (steel), 1 (cement), 0.5 (paper), and 0.75 (chemicals)
	Material efficiency	- Industrial production reductions based on material efficiency - Factors: 0.27 (steel), 0.8 (cement), 1 (paper), and 1 (chemicals)
Building	Air conditioning temperature adjustment	- Space cooling and heating temperatures adjusted by 1 degree Celsius
	Hot water use reduction	- Residential water heating demand reduction of 25%
	Reduced use of consumer goods	- Appliance and lighting demand decrease of 17-22%
Transport	Modal shift to public transport	- 20% shift in road passenger transport to rail in urban areas
	Modal shift to non-motorized transport	- 20% shift in road passenger transport to walking and biking in urban areas
	Virtual-reality technologies	- Decrease in commute trip frequency by 20%
	Decentralization and localization of the supply chain	- Decrease in average freight transport by 20%
	Freight transport demand reduction due to reduced industrial production	- Dematerialization and material efficiency in industry affect freight transport demand by reducing industry sector production

Source: Oshiro et al. (2021), p.3.

For industry, in the LoDem scenario, dematerialization and improved material efficiency lead to significant reductions in material production, particularly in the steel sector, where crude steel production in the LoDem scenario is approximately one-third of that in the DefDem scenario.

For buildings, ESD in the LoDem for space heating, cooling, and appliances increases up to 2050 due to economic growth. However, demand for water heating decreases slightly due to a declining population. By 2050, appliance ESD is projected to be 50% higher than the 2010 level in the DefDem scenario. In the LoDem scenario, ESD for space heating, cooling, water heating, and other appliances decreases by approximately 8%, 25%, and 17% compared to the DefDem scenario, respectively. The reduction in appliance ESD in the LoDem scenario helps offset demand increases after 2020.

In the transport sector, several measures lead to a 27% reduction in total passenger transport demand and a 26% reduction in freight transport demand by 2050 compared to the DefDem scenario. Modal shifts from road to rail in passenger transport contribute to a 43% reduction in road transport by 2050.

Reducing energy service demand presents challenges for the transformation of the energy supply sector. In the LoDem scenario, carbon sequestration experiences a significant reduction, dropping to nearly half of what is observed in the DefDem scenario under FullTech. The decline in carbon sequestration in the LoDem scenario primarily stems from decreased steel and cement production. However, carbon sequestration in energy supply sectors also decreases significantly, especially in the FullTech scenario. This drop is mainly attributed to reduced reliance on CCS in power generation due to decreased electricity demand. In contrast to CCS, the expansion of renewable energy sources is crucial for meeting emission reduction targets.

2.1.14 Millward-Hopkins and Oswald (2023)[22]

Millward-Hopkins and Oswald (2023, pp.e147-e154) discuss the relationship between energy and income inequality in the context of LED scenarios. They argue that reducing global energy inequality is crucial for maintaining a safe climate and achieving decent living standards for all. Their work is notable for its socio-economic angle, highlighting the need for drastic reductions in global energy inequality to support sustainable energy use and equitable growth. It differs from other studies by focusing more on the socio-political aspects of energy use and climate change, rather than on technological or economic factors.

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22) This section summarizes Millward-Hopkins and Oswald (2023), pp.e147-e154.

The authors highlight that traditional climate mitigation scenarios often rely on large-scale deployment of negative-emissions technologies, which have limitations and pose risks to biodiversity and food systems. As an alternative, they explore LED scenarios and minimum energy levels required for decent human well-being.

The study notes that achieving these goals would require even greater efforts to reduce inequality in the Global South, unless there is a full convergence of living standards between the Global South and the Global North. This convergence would necessitate substantial reductions in consumption in the Global North, beyond what is assumed in LED scenarios.

This study examines LED scenarios as a means to address the challenges of climate change while ensuring human well-being. It specifically analyzes two models: a global model by Grubler et al., and a UK-specific model by Barrett et al. The global model provides data for both the Global North and South, while the UK model offers insights into a high-income country's context. It highlights substantial inequalities in energy use, with the top 1% of the Global South using around 35 times the energy of the bottom 10%, compared to a 12-fold difference in the Global North, and six-fold in the UK. The Gini coefficient, measuring inequality, is higher globally (0.58) than in the Global South (0.45), suggesting more equal energy distribution regionally. The methods involve combining data on current energy consumption inequalities with LED scenarios for 2050. The study assesses the potential impact on global populations, especially regarding access to the minimum amount of energy needed for decent living if current inequalities persist.

The study focuses on the Gini coefficient, a measure of inequality ranging from 0 (perfect equality) to 1 (perfect inequality), to quantify energy inequality. The analysis includes both direct and indirect energy use, providing a comprehensive view of energy services and their relationship with basic needs.

Through this method, the study aims to estimate the necessary reductions in current Gini coefficients by 2050 that would allow everyone to achieve decent living standards in terms of energy consumption. The approach assumes the future distribution of energy consumption will resemble current patterns. This analysis is critical in understanding the interplay between energy consumption, inequality, and the fulfillment of basic human needs in the context of sustainable development.

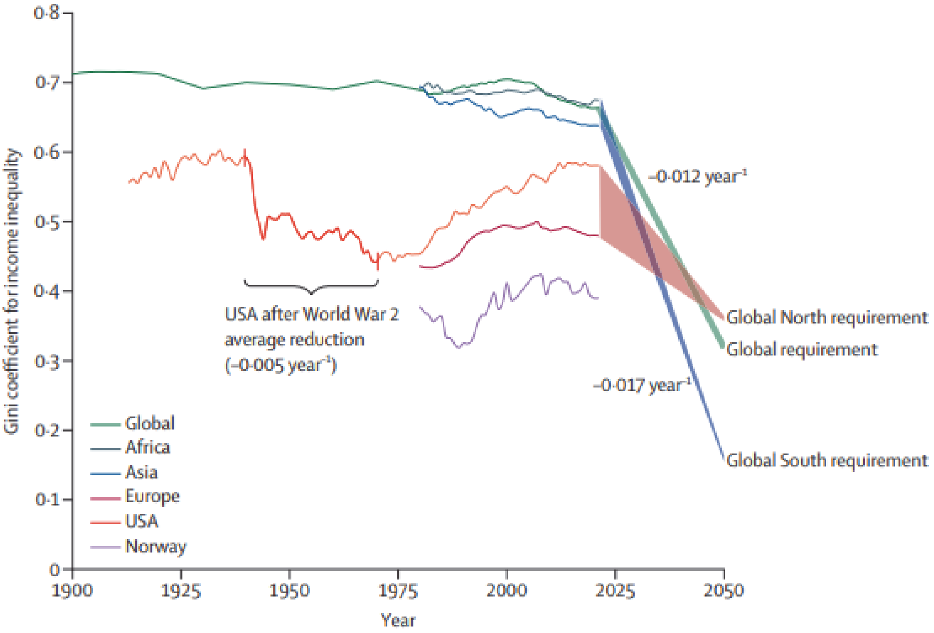
The findings suggest that achieving a climate-safe future with universal decent living standards will likely require significant reductions in both income and energy inequality. If global energy consumption is reduced without addressing these inequalities, over 4 billion people may not have access to the energy required for a decent standard of living. To prevent this, the study indicates that global income inequality, as measured by the Gini coefficient, would need to decrease significantly, potentially to levels seen in the most egalitarian European countries.

Average energy consumption in the Global South is 18.1 GJ/capita, but less than 5 GJ for the bottom 10% and 150 GJ for the top 1%. There's an overlap in consumption between the top 20% in the Global South and the bottom 50% in the Global North. Over half of the Global South's population currently falls short of Decent Living Energy (DLE) thresholds. If energy inequality persists up to 2050, a significant portion of the Global South's population will consume less than the DLE standard, even assuming slight increases in average consumption.

To ensure everyone in the Global South is above the DLE threshold, the energy Gini coefficient needs to be reduced significantly. Alternatively, average consumption must converge with that of the Global North, alongside smaller reductions in energy inequality. In the Global North and the UK, ensuring everyone is above the DLE level requires less dramatic reductions in energy inequality due to higher per-capita energy use assumed in LED scenarios.

The study concludes that achieving decent living standards for all on an LED pathway requires major reductions in energy inequality, especially in the Global South. As energy consumption is tied to income, this implies large reductions in income inequality are also necessary. The required changes are historically unprecedented, indicating the need for significant transformation in global economic systems and policies.

Figure 21. Income inequality and reductions required for well-being and climate safety



Source: Millward-Hopkins and Oswald (2023), e153.

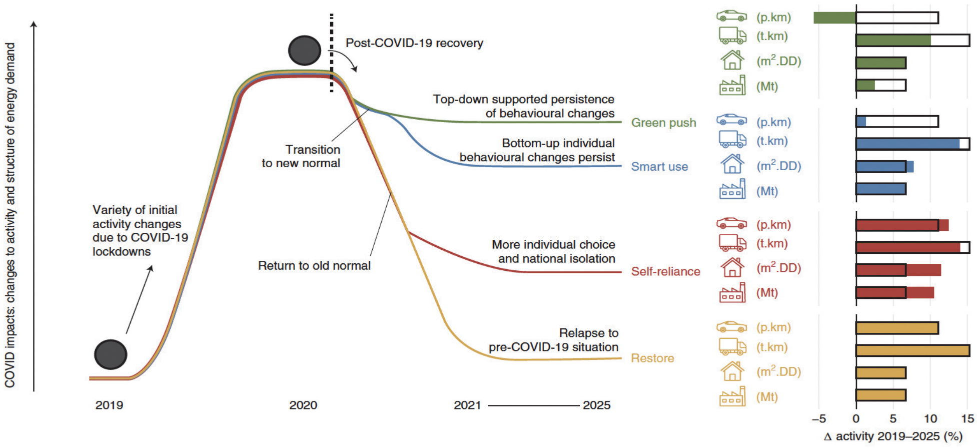
2.2 Recent Research on Demand and Transformation in MESSAGEix

There is an increasing number of research studies applying Integrated Assessment Models to analyze demand-side approaches and low energy demand scenarios. In the previous section, we saw how Grubler et al. (2018) applied the MESSAGEix model to describe the kind of policy and socio-economic and technological measures necessary to realize a LED scenario, and characterized the kinds of global trends in energy demand reduction. The narrative driving LED scenarios and key results have established the foundation for more LED discussions globally. Moreover, the MESSAGEix-GLOBIOM model is widely used for energy analysis in various sectors.

Kikstra et al. (2021, pp.1114-1123) presented global scenarios on the impact of persistent demand changes due to COVID-19 by using MESSAGEix-GLOBIOM. This study collected data on the impact of COVID-19 on demand in various sectors.

The paper focused on key demand sectors, such as transportation, buildings, and industry. The projected pathways suggest final energy demand reductions of 1–36 EJ per year by 2025 and cumulative CO_2 emission reductions of 14–45 $GtCO_2$ by 2030. A recovery with energy-efficient practices in various sectors mitigates climate challenges, reduces carbon prices by 19%, cuts energy supply investments by USD 1.8 trillion by 2030, and eases the rapid scaling of renewable energy technologies.

Figure 22. Post-COVID recovery pathways



Source: Kikstra et al. (2021), p.1116.

Mastrucci et al. (2021, pp.1-26) utilized MESSAGEix-Buildings and developed global residential scenarios under shared socio-economic pathways (SSPs) 1–3, assessing building stock evolution, energy demand, and CO_2 emissions for space heating and cooling. Projected CO_2 emissions for space heating decrease by 34.4–52.5% by 2050, driven by energy efficiency and electrification. However, space cooling demand surges globally by 58.2–85.2% due to varying energy-efficient practices and cooling patterns, especially in developing countries. This study enhances building sector knowledge for integrated assessment in global climate change mitigation and sustainable development.

Yeh et al. (2022) highlighted the lack of access to high-quality data on current and historical travel demand, arguing the paucity of quality data hinders sustainable transitions. It advocated for interdisciplinary collaboration in open data, data science, behavior modeling, and policy analysis to address uncertainties and provide evidence-based solutions. The work proposed the International Transport Energy Modeling Open Data project as a potential resource to facilitate such efforts.

Mastrucci et al. (2023, pp.761-792) reviewed energy demand reduction modeling exercises in the building sector. This review includes MESSAGE-Buildings and other building models. Current building models have limitations in assessing LED transformations. This review evaluates building sector models at different scales and highlights best practices and gaps. To improve building sector models for LED transformations, there is a need for more data on social and behavioral interventions, including individual behaviors and participatory governance. Infrastructural interventions are often oversimplified, overlooking underlying dynamics. While demand-side technologies, like energy-efficient appliances and passive buildings, are integrated in building sector models, a focused approach on energy services and an improved representation of technology is necessary. In addition, understanding and incorporating the dynamics of various megatrends, including digitalization and the circular economy, is crucial for comprehensive building sector modeling and informed decision-making toward a sustainable LED future.

2.3 Review of Energy Status and Demand-side Policies

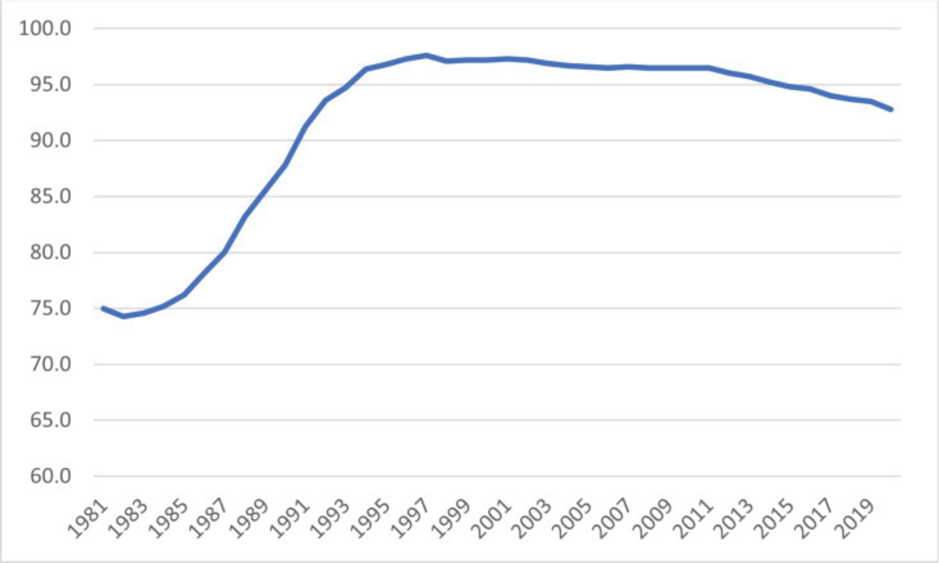
In previous studies, energy demand-side measurements showed significant potential for GHG emissions reduction and economic benefits. In terms of policy, energy demand-side approaches have received increasing attention from Korea, Europe, and other countries. This is due to factors such as energy supply and demand instability and international energy price fluctuations (due to the Russia-Ukraine war and others) and major instruments for GHG emission reductions to achieve carbon neutrality.

2.3.1 Korea

Korea is a country with a significant dependence on energy imports. The country’s rate of energy dependence on imports was estimated at approximately 94.3% (KEEI, 2023a, pp.1-137) in 2022, and it remained over 95% in the 2010s.

Figure 23. Korea's energy dependence on energy imports

(Unit: %)

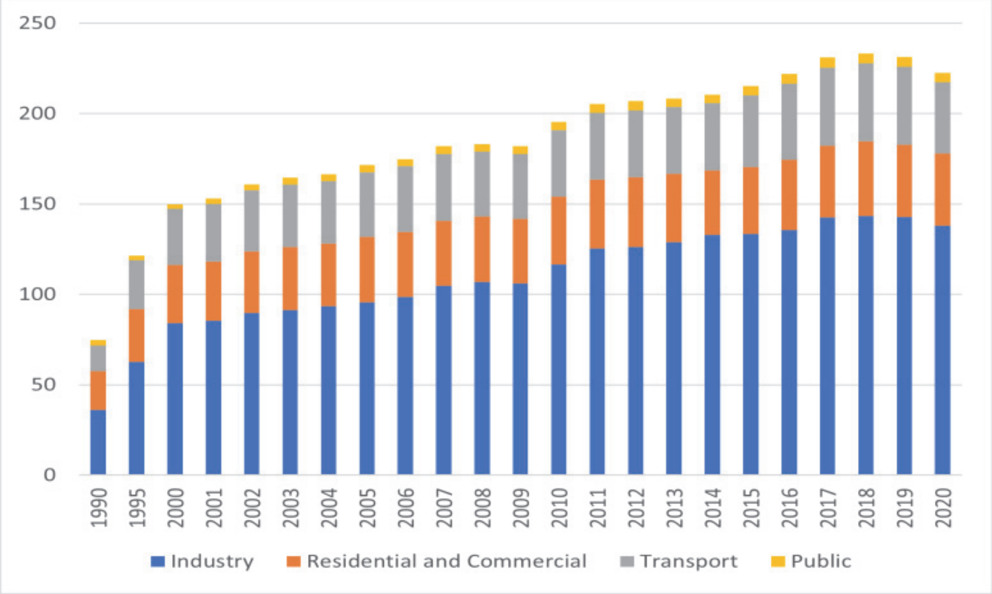


Source: KESIS (November 15, 2022), "Energy Dependence on Import (Annual)", accessed on January 29, 2024.

Therefore, energy security, which ensures a stable supply of energy commodities and maintains a balance between energy supply and demand, has been an important policy objective. To achieve this objective, the country has been promoting energy conservation and efficiency measures in key sectors such as industry, transport, and building.

Figure 24. Final energy consumption by sector

(Unit: MTOE)



Source: KESIS (2022.11.15), "Final Energy Consumption by Sector (Annual, Calorie-based)", accessed on January 2, 2024.

In terms of final energy consumption, Korea ranked 10th in the world with 181.7 MTOE in 2021[23] and is the 5th largest importer of oil and the largest importer of natural gas in the OECD (KEEI, 2022, pp.1-285).

Oil accounted for 49.3% of the country's final energy consumption in terms of TOE in 2021, followed by electricity, coal, and LNG and city gas at 19.3%, 13.4%, and 11.7%, respectively (KEEI, 2022, pp.280-285). Approximately 61.3% of oil is used in the industrial sector, and 33.4% is used in the transport sector. In the industrial sector, the growth of the petrochemical industry has led to an increase in the consumption of naphtha and other products. Industry utilizes 51.7% of electricity, while 41.7% of electricity is used in the residential and commercial sectors. Coal is characterized by the fact that most of it, 99%, is utilized in the industrial sector. Regarding the final energy consumption by consumption side, the industrial sector

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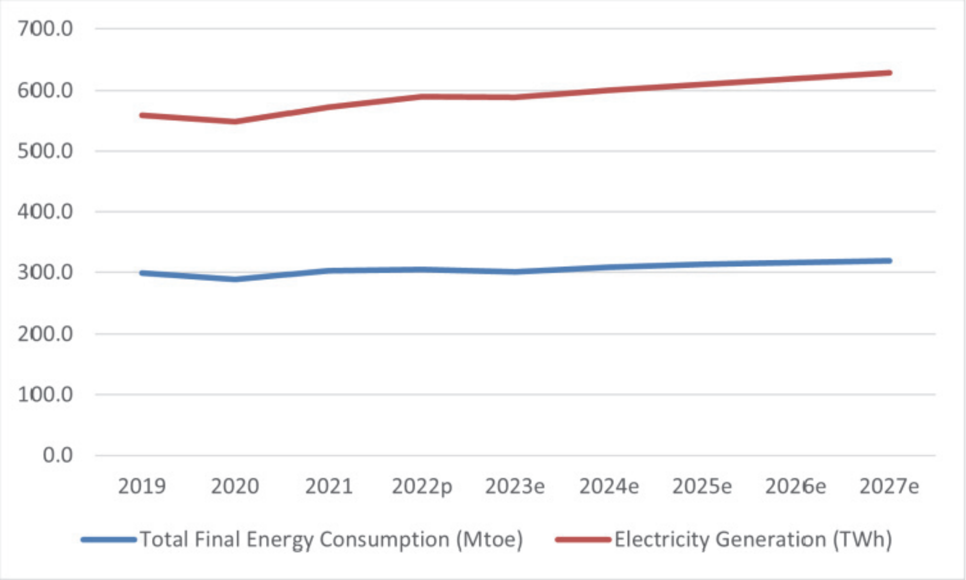
[23] IEA (August 2, 2023), "World Indicators (Edition 2023)", accessed on November 24, 2023.

accounts for 63.3%, followed by the transportation and residential/commercial sectors with 16.9% and 17.4%, respectively (2021, Energy Balance TOE) (KEEI, 2022, pp.280-285).

The Medium-term Energy Demand Outlook (2022–2027) projects that Korea's final energy consumption will continue to increase at an average rate of 0.8% between 2022 and 2027 (KEEI, 2023b, pp.7-114).

Figure 25. Mid-term projections of final energy demand and electricity generation (2022-2027)

(Unit: MTOE, TWh)



Source: Authors' analysis based on KESIS (2023b), pp.7-114.

Moreover, the importance of understanding energy demands and designing appropriate policies has increased. It is necessary to consider the recent rapid deployment of electric vehicles and the adoption of AI and ICT technologies, which have led to a broad range of energy demand changes as well as demographic changes due to the low fertility rate and population aging in Korea. Such changes, including technological and demographic changes, are likely to change the demands of different energy sources as well as the energy demand. Additionally, demographic structural changes due to low fertility and aging populations would affect future energy demand and the consumption of each energy carrier.

In recent years, the government has further emphasized market-based energy efficiency improvement in demand-side sectors, such as industry, residential and commercial buildings, and transport sectors (Government of Korea, 2022). This can help reduce the burden of energy demand by increasing efficiency in industry, buildings, and transport, thereby easing the pressure on the supply side.

In the industry sector, the government emphasized the promotion of voluntary agreements that set mitigation targets and methods for energy conservation and efficient use, mandatory energy efficiency resource standards, policy innovation, and incentives. In the building sector, policy measures such as expanding the energy cashback program nationwide and transferring the energy audit authority to local governments for large existing buildings are suggested.

Lastly, in the transportation sector, major strategies include the optimization of electric vehicle efficiency, widespread adoption of electric vehicles with superior driving efficiency, and the enhancement of energy efficiency through innovation in transportation infrastructure.

Table 3. Key tasks for demand efficiency by sector

Industry	Buildings and households	Transport
Establishment of: - Energy efficiency innovation partnerships - Energy efficiency resource standards - An industrial equipment efficiency management system Enhancement of: - Industrial complex efficiency	- Provision of energy cashback incentives - Strengthened energy consumption management of existing large buildings - Increased promotion and adoption of new zero-energy buildings	- Establishment of electric vehicle efficiency management standards - Distribution of electric vehicles with superior driving efficiency - Innovation in transportation network

Source: Government of Korea (2022), p.11.

In the case of voluntary agreements, companies that consume more than 200,000 TOE of energy per year are encouraged to sign voluntary agreements on “mid- and long-term visions for carbon neutrality and efficiency innovation”, “targets for efficiency innovation”, “annual implementation plans in detail”, “incentives for achievement”, and “other cooperation matters” (Government of Korea, 2022).

In particular, The Korea Energy Efficiency Partnership (KEEP) 30 is an agreement between 30 energy-intensive companies and the government to provide incentives for achieving energy efficiency improvements between 2023 and 2027.24)25) The goal is to achieve an average annual improvement of at least 1% per unit of energy over five years. Depending on the evaluation result, support is provided for technology development, tax incentives, and infrastructure building packages.26) Energy cashback programs offer tiered incentives to participating customers who use residential electricity and reduce their consumption by 3% or more compared to the average for the same month in the previous two years.27) These policies represent efforts to voluntarily change the behavior of both industries and households.

As the country has established ambitious mitigation targets and announced the Net Zero target by 2050, there has been increased interest in and attention to DR policies for demand responses. Particularly, the First National Basic Plan for Carbon Neutrality and Green Growth, announced in 2023 (Government of Korea, 2023, pp.16-177), considers policy approaches on the demand side of the electricity and transport sectors. In policy design, sectoral energy demand projections are considered in establishing national and sectoral emission projections, and demand-side responses are considered important in achieving carbon neutrality. Experts and policymakers understand that demand-side approaches can reduce the necessity of advanced and relatively expensive technologies, such as CCS. This could provide opportunities to meet national targets in less expensive ways.

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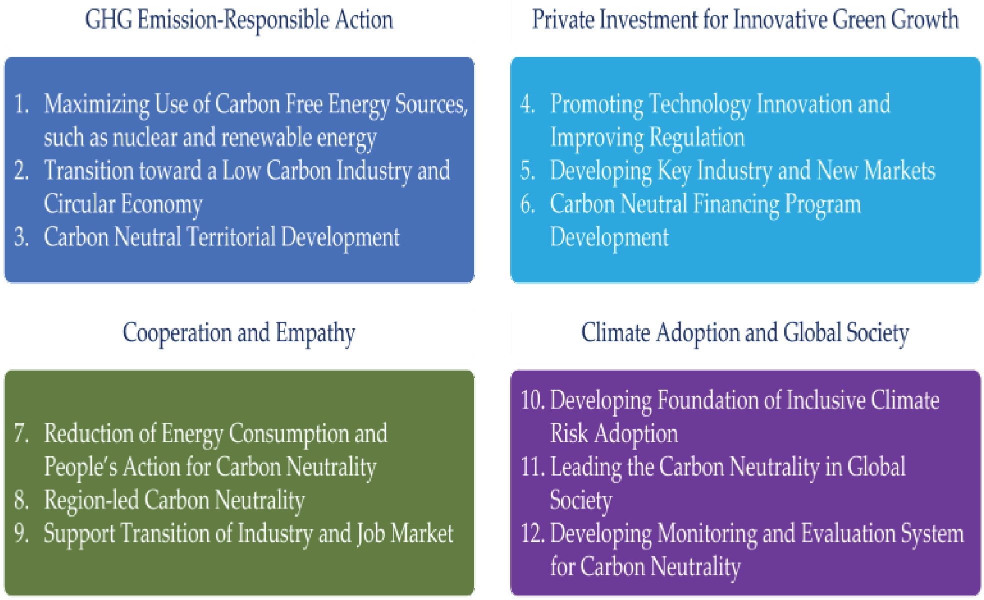
24) Korea Energy Agency (December 1, 2023), “KEEP 30 (Energy Efficiency Partnership)”, accessed on December 28, 2023.

25) Ki (October 19, 2022), “MOTIE Signs ‘Energy Efficiency Partnership with the 30 Largest Energy-Intensive Companies”, accessed on October 30, 2023.

26) Korea Energy Agency (December 1, 2023), “KEEP 30 (Energy Efficiency Partnership)”, accessed on December 28, 2023.

27) KEPCO (June 26, 2023), “Introduction of Energy Cashback Program”, accessed on September 6, 2023.

Figure 26. The National Basic Plan for Carbon Neutrality and Green Growth



GHG Emission-Responsible Action

1. Maximizing Use of Carbon Free Energy Sources, such as nuclear and renewable energy
2. Transition toward a Low Carbon Industry and Circular Economy
3. Carbon Neutral Territorial Development

Private Investment for Innovative Green Growth

4. Promoting Technology Innovation and Improving Regulation
5. Developing Key Industry and New Markets
6. Carbon Neutral Financing Program Development

Cooperation and Empathy

7. Reduction of Energy Consumption and People's Action for Carbon Neutrality
8. Region-led Carbon Neutrality
9. Support Transition of Industry and Job Market

Climate Adoption and Global Society

10. Developing Foundation of Inclusive Climate Risk Adoption
11. Leading the Carbon Neutrality in Global Society
12. Developing Monitoring and Evaluation System for Carbon Neutrality

Source: Government of Korea (2023), p.16; Kim (2024), p.11.

Specifically, it emphasizes "energy consumption reduction and carbon-neutral practices". The country's energy consumption per unit of energy is higher than that of OECD countries, emphasizing the efficiency of energy demand and changes in society (Government of Korea, 2023, pp.29-30). This is directly related to energy demand and lifestyle changes, as previously discussed. Emphasizing that the country's energy intensity (TPES/GDP) is one of the highest in the OECD, it emphasizes efficiency in energy-intensive industries, households, buildings, and transportation sectors, as well as in ICT-managed demand management, strengthening energy conservation efforts and awareness, education, and communication (Government of Korea, 2023, pp.29-30). The demand-efficiency policies in each sector include voluntary agreements with energy-intensive enterprises, improving building efficiency, introducing electric vehicle labeling, and fuel efficiency standards for medium- and heavy-duty vans and trucks (Government of Korea, 2023, pp.29-30).

On the institutional side, ICT can be utilized to induce voluntary demand efficiency through enhanced energy tariff pricing or to achieve efficiency optimization by exchanging real-time information between electricity consumers and providers. More importantly, it emphasizes efforts to change people's behavior towards energy conservation, such as adhering to recommended heating and cooling temperatures for buildings, participating in energy conservation campaigns, adopting carbon-neutral practices, and increasing incentives for such activities and efforts. Additionally, to bring about long-term change, it aims to lay the foundation for climate change and carbon neutrality education in schools and society at large and to provide information and activate communication on how to practice carbon neutrality in everyday life.

Table 4. Energy demand-related plans in the National Basic Plan for Carbon Neutrality and Green Growth

Improve energy demand efficiency (industry, household/building, and transport)	
Industry	Voluntary agreement with excessive energy consuming business entity
Household/ Building	Efficiency improvement of excessive energy-consuming buildings, promote energy cashback program
Transport	Electric Vehicle Labeling
ICT-based Policy Reform	
Smart Grid	Interactive real-time information exchange between suppliers and consumers for optimizing energy efficiency and consideration of the introduction of “prosumer”
Energy Market	Promote voluntary energy demand efficiency improvement by strengthening energy pricing structure
Energy conservation by enhancing energy saving efforts in all sectors and shifting public perception	
Public	Cooling and heating temperatures, turning off landscape lighting
Private	Energy conservation campaign (“Energy Diet Supporters”)
Community	Expanding best practices (carbon neutrality community)
Incentive	Expanding incentives and participation opportunities (Carbon Neutrality Point System)
Awareness transformation by establishing the foundation for implementing climate change and carbon neutrality education in school and the society	
School	Based on the revised curriculum for elementary and secondary schools with enhanced climate and ecological environment education, lead schools to become a place for learning carbon neutrality
Foundation	Expanding carbon neutrality education and establishing foundations in cooperation with environmental organizations, designating environmental education cities, strengthening the environmental educator system
Better communication by operating platforms to provide information and communicate about carbon neutrality policies and daily practices	
Promotion	Promote policies and campaigns through media and public relations resources
Information	Share domestic and international trends of carbon neutrality, private sectors’ best practices, the up-to-date trends, and policy progress
Communica tion	Online campaigns, collecting public suggestions and opinions to spread life practices, sharing information on carbon neutrality practices

Source: Modified by the authors based on Government of Korea (2023).

Previously, Korea’s energy demand policies have emphasized responses to increasing energy consumption, global energy crisis, and economic insecurity. The Energy Use Rationalization Act, enacted in 1980, emphasizes energy supply and demand stability and efficient energy use.28) The Act was revised in response to changes in the national and global energy and economic environments. However, recent policy changes indicate that the country's energy policy focus is shifting from being supply-oriented to demand-focused. It is also noticeable that it not only simply indicates improving energy efficiency in energy-intensive sectors (e.g, replacing high-efficiency motors) but also brings about changes in the entire society.

2.3.2 European Union (EU)

The European Union (EU) has been emphasizing energy consumption reductions and, in particular, has accelerated its efforts since the Russia-Ukraine war. The EU facilitates the reduction of energy-related expenditures, responds to issues related to a stable energy supply and imports, and accelerates the achievement of the EU's climate target (Shim, 2023, pp.5-12). Various measures and options, including Energy efficiency and behavioral changes, are considered to reduce energy demand. As part of the "REPowerEU" package, the "EU Save Energy Plan" has been proposed to support the use of public transportation and efficient appliances while reducing the use of cooling devices. Additionally, it includes enhanced rules on the energy performance of buildings and energy audits.29) Furthermore, the "2023 Energy Efficiency Directive" proposed enhanced energy efficiency targets to reduce further energy demand by 11.7% relative to the 2020 reference scenario by 2030. This indicates a 40.5% reduction in primary energy consumption and a 38% reduction in final energy consumption by 2030 compared to the 2007 EU Reference Scenario, which would limit the total EU energy consumption to no more than 992.5 MTOE of primary energy and 763 MTOE of final energy by 2030 (Scheuer and Bere, 2023, pp.4-8).30)

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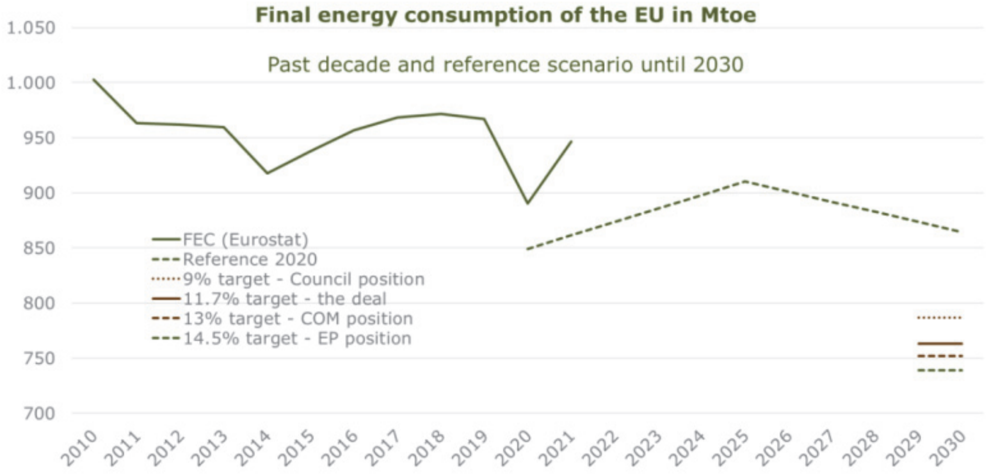
28) Korean Law Information Center, "Energy Use Rationalization Act".

29) European Commission (May 18, 2022), "REPowerEU: A Plan to Rapidly Reduce Dependence on Russian Fossil Fuels and Fast Forward the Green Transition", accessed on October 3, 2023.

30) European Commission (February 24, 2024), "Energy Efficiency Directive", accessed on February 29, 2024.

Figure 27. EU's final energy consumption target by 2030



Source: Scheuer and Bere (2023), p.5.

The Directive requires EU member states to set objective criteria such as energy intensity and energy-saving potential, considering national circumstances, to achieve EU targets. It also signals a strong policy drive to achieve energy demand reduction targets by issuing corrections, known as a "gap-filling mechanism", if a country's contributions do not meet the EU target.[31]

The following items should be considered when establishing a national energy efficiency contribution (European Union, 2023, pp.28-35).

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[31] European Commission (February 24, 2024), "Energy Efficiency Directive", accessed on February 29, 2024.

Table 5. Factors and circumstances for national efficiency contributions

Efficiency-related factors	Early efforts and actions in energy efficiency
	Equitable distribution of efforts across the Union
	Energy intensity of the economy
	Remaining cost-effective energy-saving potential
National circumstances affecting energy consumption	GDP and demographic evolution and forecast
	Changes of energy imports and exports, developments in the energy mix and the deployment of new sustainable fuels
	Development of all sources of renewable energies, nuclear energy, carbon capture and storage
	Decarbonization of energy intensive industries
	the level of ambition in the national decarbonization or climate neutrality plans
	Economic energy saving potential
	Current climate conditions and climate change forecast

Source: European Union (2023), p.34.

Specifically, the EU has included the “Energy Efficiency First Principle” in the Revised Energy Directive, providing a legal basis for guiding energy policy and investment decisions that prioritize improving energy efficiency and lowering production costs. It emphasizes the benefits of reducing energy demand to lower the level of investment required for the transition to renewable energy, sustainable use of limited resources, and resilience of the EU energy system.[32]

Table 6. “Energy Efficiency First Principle” in EU legislation

Requirement 1	Applying cost-benefit assessment methodologies, including the assessment of the benefits of energy efficiency measures
Requirement 2	Identifying an entity, which take responsibility of monitoring the application of the principle
Requirement 3	Reporting the application of the principle to the Commission

Source: European Commission (December 24, 2023), “Energy Efficiency First Principle”, accessed on January 11, 2024.

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32) European Commission (December 24, 2023), “Energy Efficiency First Principle”, accessed on January 11, 2024.

The principle has been given legal status through its inclusion in the Revised Directive, enacted in October 2023. It emphasizes that member states must ensure that "energy efficiency solutions", including demand resources or system flexibility, are valued at least 100 million each (175 million for transport infrastructure projects) in their plans, policies, and major investment decisions in the energy system and non-energy sectors that may affect energy consumption and efficiency in key sectors (European Union, 2023, pp.32-33).

2.3.3 Germany

Germany has been promoting significant long-term reductions in energy demand for energy transition and climate response, even beyond the EU's target. The "New Energy Efficiency Act", passed by Germany's Lower House of Parliament in September 2023, sets long-term targets for both public and private energy consumption reduction. This act targets a higher final energy consumption reduction than the EU (26.5% reduction by 2030 from 2008).[33] These include important policy measures for reducing energy consumption. First, new heating systems must be operated using at least 65% renewable energy since the beginning of 2024. Additionally, companies that consume 15 GWh or more annually require the establishment of an energy or environmental management system. Companies consuming more than 0.5 GWh a year are required to conduct energy audits. Detailed regulations for data centers and IT technology operators include a minimum of 50% of electricity from renewable sources without subsidies, the sharing of energy-related information, and the use of waste heat.[34][35]

The "2023 Climate Action Program" (Federal Ministry for Economic Affairs and Climate Action Germany, 2023) of Germany included various energy efficiency improvement and energy consumption reduction measures.

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[33] Alkousaa and Kraemer (September 22, 2023), "Germany Passes Law to Make Energy Savings Compulsory", accessed on October 3, 2023.

[34] Allen and Overy (September 29, 2023), "Update – Germany Tightens Energy Efficiency Requirements: New Challenges for Companies and Data Centers", accessed on October 10, 2023.

[35] Alkousaa and Kraemer (September 22, 2023), "Germany Passes Law to Make Energy Savings Compulsory", accessed on October 3, 2023.

Table 7. Examples of measures for energy efficiency improvement and energy consumption reduction in the 2023 Climate Action Program

Sector	Measures
Building	The Efficiency House 55 (new standard for new building); Federal funding for efficient buildings (renovate existing buildings); Public Building Initiative (energy efficiency specifications for climate-neutral new buildings/extensions and the renovation of buildings of the Federal government); Energy-efficient urban redevelopment
Industry	Federal funding for energy and resource efficiency in the economy
Transport	Funding for efficiency measures for trailers
Digitalization	Increasing efficiency through automated and connected driving

Source: Modified by the authors based on Federal Ministry for Economic Affairs and Climate Action Germany (2023).

2.4 Implications

On the policy side, many countries, including Korea, the EU, and Germany, are making efforts to change their energy consumption structures, and various policies are being introduced. Their common characteristic is that they focus their efforts on the energy-intensive sectors of industry, buildings, and transport, and energy efficiency improvements in each of these sectors are considered an important aspect of their efforts. Historically, energy efficiency improvements in government policy have generally come to the fore during energy crises. In the case of the Republic of Korea, the country’s significant dependence on energy imports and the global energy crisis, including the oil shock, have made energy security an important consideration and emphasized the need to improve energy efficiency. In the EU, many policies to improve energy efficiency have emerged as energy supply and demand have been affected by the Russia-Ukraine War. However, it is noteworthy that the demand side has recently been emphasized within the framework of achieving carbon neutrality rather than just responding to energy supply and demand issues. In its National Basic Plan for Carbon Neutrality and Green Growth, the Republic of Korea has identified “Reducing Energy Consumption and Carbon-Neutral Practices” as one of its 12 core tasks, emphasizing not only efficiency improvements in key sectors but also awareness-raising and strengthening energy conservation efforts across all sectors. It is characterized by its emphasis not only on improving energy efficiency in existing buildings, industry, and transport but also on people‘s lifestyle changes, These changes include adopting more eco-friendly or low-carbon diets, altering uban structures, and transforming the economy and society through enhanced ICT and digitalization efficiencies.

Moreover, the impacts of climate change on energy demand should not be ignored. Climate change and rising global temperatures would lead to the increase in severity and frequency of extreme weather events, including heat waves, which could affect energy consumption. For instance, heat waves significantly increase the electricity consumption in Italy.36) It would affect the possibility of the achievement of low energy demand. Particularly, about half of the global final energy consumption is due to cooling and heating (IRENA, 2023, p.87), and even in Europe, about half of the total energy consumption is due to cooling and heating energy consumption.37) This study focuses on cooling and heating energy consumption, which accounts for about half of the total energy consumption and is expected to be highly affected by climate change.

Recently, there has been an increasing number of studies on energy demand. The IPCC (2022) includes a low demand scenario as one of the main IMPs, and NGFS, a group of central banks and supervisory agencies, adds a low demand scenario to the transition scenarios in Phase 4. As shown in the literature, key measures on the demand side include energy efficiency, dematerialization, modal shifts in transport, and digitalization. While some integrated assessment models, such as MESSAGEix-GLOBIOM, REMIND-MAgPIE, and AIM, have been used to analyze low energy demand, many studies have largely focused on specific sectors (industry, buildings, transport, etc.).

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36) Bloomberg (July 18, 2023), “Italians’ Electricity Use Surges as Heat Wave Blankets Country”, accessed on March 28, 2024.

37) Eurostat (February 3, 2023), “Heating and Cooling from Renewables Gradually Increasing”, accessed on March 27, 2024.

3

Development and Update of the Global CGE Model

3.1 Structure of the Global CGE Model

This study applies a recursive dynamic Computable General Equilibrium (CGE) model to analyze the economic impacts of LED scenarios. The model determines market equilibrium levels in consideration of the interactions between economic agents and markets (Burfisher, 2017, pp.8-57). The global CGE model is composed of a system of equations and delivers a series of equilibrium conditions, including conditions for factor and commodity markets (Jung, Kim, and Moon, 2021; Kim et al., 2023, pp.16-22).

The model applies the latest GTAP 11 Power Database, which was released in December 2023 (Aguiar, Angel et al., 2023, pp.7-13). The GTAP 11 Power Database includes detailed information of 12 different power technologies, including transmission and distribution technologies, so the effects of promoting renewable electricity can be analyzed with this database. In addition, the updated database expands regional coverage and includes total 160 country/region with 141 countries and 19 aggregate regions as well as 76 products and services, including 12 detailed power technologies (Aguiar, Angel et al., 2023).

The purpose of the present study is to analyze LED scenarios and better grasp their potential to facilitate the realization of Net Zero in countries, such as Korea. The work integrates 160 countries/regions into 17 aggregated countries/regions. It separates Korea, the United States, Japan, and Canada as individual regions, and groups other countries in aggregate categories based on geographical characteristics (Other East Asia, Western Europe, Australia/New Zealand, Central and Eastern Europe, etc.).

Table 8. Regional classifications in the CGE model

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

Note: The analysis follows the regional classification of the FUND Model in order to utilize the parameters of the climate module and the damage function.

Source: The authors, based on the FUND model (MimiFUND, 2020.7.14) accessed on May 17, 2023.

Furthermore, this work aggregates 76 sectors into 21 composite sectors. To better analyze energy consumption, the coal, oil, gas, and petroleum and coal product sectors were kept as is. For the electricity sector, the study aggregated 12 power technologies into three composite sectors: renewable electricity, nuclear electricity, and non-renewable electricity. Solar, wind, and hydro electricity are considered renewable electricity. Nuclear power technology is considered separately. Other power technologies are considered non-renewable electricity.

Table 9. Sectoral classifications in the CGE model

Sector	Description
Ely	(non-renewable) Electricity
COA	Coal
OIL	Oil
GAS	Gas
P_C	Petroleum and coal products
AGR	Agriculture
REN	Renewable electricity
NUC	Nuclear electricity
Mineral	Extraction
Food	Food (meat, vegetables, dairy products, food products, beverages)
Cloth	Textiles, apparel, leather
Paper	Wood products, Paper products
Chemical	Chemical products, basic pharmaceuticals, rubber and plastics, mineral products
Metal	Iron and steel, non-ferrous metals, manufacture of fabricated metal products
ICT	Manufacture of computer, electronic, optical products, and electric equipment
Vehicle	Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment
Machine	Manufacture of machinery and equipment, and other manufacturing
Construct	Construction
Service	Service
Trans	Transport (land, water, air transport)
Dwell	Dwellings (ownership of dwellings)

Source: The authors.

Moreover, in this updated version of the dataset, detailed information on non-CO_2 greenhouse gases is included. In the previous version, information on non-CO_2 emissions was limited to CH_4, N_2O, and aggregated F-gases, but this update provides more detailed data on individual F-gases, HFCs, and PFCs. The CGE model aggregates the individual non-CO_2 greenhouse gases from the GTAP 11 database into six major types of greenhouse gas (N_2O, CH_4, NF_3, SF_6, PFCs, and HFCs). The model is calibrated using updated SSP scenarios from the EU Navigate project.38) These scenarios include population and GDP projections in consideration of the impacts of COVID-19.

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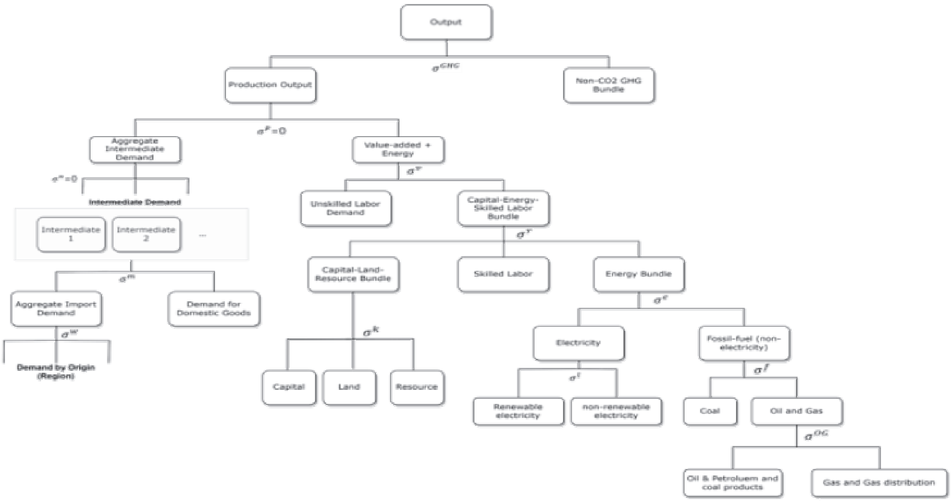
38) EU Navigate (September 22, 2023), "SSP Update", accessed on October 31, 2023.

The global CGE model establishes a system of equations and determines equilibrium conditions for macroeconomic aggregates and factor and commodity markets. The model adopts a capital dynamic structure, which differentiates between "old" and "new" capital with elasticities of substitution. It considers Constant Elasticity of Substitution (CES) production functions.

Figure 28. Production nesting structure



Source: The authors.

Table 10. Key parameters

Parameter	Value
Substitution between Output and non-CO_2 emissions	0.02~0.1 depending on sectors
Substitution between unskilled labor and KTRE Bundle	GTAP (esubva): (for new) 0.2 for coal, oil, and mineral; 1.26 for ely, p_c, ren, and nuc; 0.48 for gas; 0.254 for agr; 1.363 for service; 1.4 for construct; 1.68 for trans; 1.12 for food; 1.26 for cloth, paper, chemical, metal, ICT, vehicle, machine, and dwell
Armington elasticity (domestic vs. import)	GTAP (esubdm): (for new) 0.9~6.35 depending on sectors
Armington elasticity (Import sources)	GTAP (esubm): (for new) 1.8~34 depending on sectors
Substitution among KTR bundle, energy, and skilled labor	0.535 for coal, oil, p_c; 0.396 for gas, ely, ren, nuc; 0.029 for agr; 0.35 for mineral; 0.391 for food; 0.17 for cloth; 0.372 for paper; 0.038 fo chemical; 0.29 for metal; 0.246 for ICT; 0.091 for vehicle; 0.118 for machine; 0.105 for construction; 0.404 for service; 0.449 for trans; 0.654 for dwell
Substitution among capital, land, and natural resources	0.2 for new vintage; 0.06 for old vintage
Substitution between electricity and other energy inputs	2 for new vintage; 0.6 for old vintage 0 for fossil fuel
Substitution between coal and liquid	0.55 for new vintage; 0.06 for old vintage 0 for fossil fuel
Substitution between oil and gas	1 for new vintage; 0.125 for old vintage 0 for fossil fuel

Note: For old vintage, the elasticities of new vintage are multiplied by 0.3.
Source: The authors.

The model separates electricity technologies into three categories: non-renewable electricity, renewable electricity, and nuclear electricity. For renewable energy technologies, the study applies a 15% learning rate to the productivity of those technologies.

The impacts of climate change and the global temperature increase can affect energy consumption through various channels, including the changes in cooling and heating energy demand, and these could affect the global and regional energy demand. In order to analyze such impacts on energy demand, a climate module and a function for estimating the energy demand due to climate change or temperature increase are necessary. In this regard, the study develops and applies the climate module and the function for calculating the cooling and heating energy demand changes due to temperature increases.

3.2 Development of the Climate Module[39)]

In order to analyze changes in energy consumption due to global/regional temperature changes, the study incorporates a climate module from the FUND model, an integrated assessment model.[40)] To apply the parameters from the FUND model, the study basically follows the model's existing regional classifications but additionally distinguishes Korea as a separate region. The climate module and associated parameters of the FUND model are directly adopted, and the study assumes that Korea and Japan have the same parameter values for the climate module.

First, the FUND model's climate module[41)] calculates carbon dioxide concentrations in the atmosphere using the equation (1). It calculates the carbon concentration. *C* refers to concentrations in ppm, *E* represents global carbon emissions, *t* stands for time, and *pre* indicates pre-industrial levels. The initial carbon dioxide concentration determined through the FUND model was 310.75 ppm, but this value is outdated. Thus, we updated the value to 405.22 ppm in 2017 to reflect the findings of Lan, Tans, and Thoning (2024).

$$c_t = c_{t-1} + E_{t-1} - \beta\left(c_{t-1} - c_{pre}\right) \qquad \text{Equation (1)}$$

Next, the module utilizes the 5-box model for calculating concentrations. It considers the decay of carbon dioxide. ρ denotes the decay rate of the boxes. The summation of all boxes provides the concentration of carbon dioxide in the atmosphere.

$$BOX_{i,t} = \rho_i BOX_{i,t-1} + 0.000471 a_i E_t \qquad \text{Equation (2)}$$

$$C_t = \sum_{i=5}^{5} a_i BOX_{i,t} \qquad \text{Equation (3)}$$

After calculating carbon dioxide concentrations, the climate module estimates radiative forcing. Radiative forcing considers carbon dioxide as well as methane

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[39)] The equations and parameters from MimiFUND (July 14, 2020) are considered when applying the climate module in the global CGE model.

[40)] MimiFUND (July 14, 2020), “MimiFUND”, accessed on May 17, 2023.

[41)] MimiFUND (July 14, 2020), “MimiFUND”, accessed on May 17, 2023.

(CH_4), Nitrous Oxide (N_2O), and sulfur hexafluoride (SF_6). All greenhouse gas emissions information comes from the global CGE model. The following equation is used to calculate radiative forcing.

$$\begin{aligned}
RF_t = {} & 5.35\ln\left(\frac{CO2_t}{274}\right) + 0.036 \times 1.4\left(\sqrt{CH4_t} - \sqrt{790}\right) + 0.12\left(\sqrt{N2O_t} - \sqrt{285}\right) \\
& - 0.47\ln\left(1 + 2.01 \times 10^{-5} CH4_t^{0.75} 285^{0.75} + 5.31 \times 10^{-15} CH4_t^{2.52} 285^{1.52}\right) \\
& - 0.47\ln\left(1 + 2.10 \times 10^{-5} N2O_t^{0.75} 790^{0.75} + 5.31 \times 10^{-15} N2O_t^{1.52} 790^{2.52}\right) \\
& + 2 \times 0.47\ln\left(1 + 2.01 \times 10^{-5} 790^{0.75} 285^{0.75} + 5.31 \times 10^{-15} 790^{2.52} 285^{1.52}\right) \\
& + 0.00052\left(SF6_t - 0.04\right) + rfSO2_t
\end{aligned}$$

Equation (4)

Based on radiative forcing information, the climate module is used to estimate global mean temperature changes.

$$T_t = \left(1 - \frac{1}{\varphi}\right) T_{t-1} + \frac{1}{\varphi} \frac{CS}{5.35\ln 2} RF_t$$ Equation (5)

$$\varphi = \max\left(\alpha + \beta^l CS + \beta^q CS^2, 1\right)$$ Equation (6)

$$RT_t = REG \times T_t$$ Equation (7)

Greenhouse gas emissions (CO_2, CH_4, N_2O, SF_6, NF_3, PFCs, and HFCs) information is calculated using the global CGE model, and then fed back into the climate module. The climate module then calculates radiative forcing and the global mean temperature change. In addition, regional factors are multiplied to calculate the regional temperature changes. This allows for an understanding of the effectiveness of policy measures such as carbon pricing and how they can contribute to limiting global temperature increases.

3.3 Damage Function (Additional Energy Consumption for Cooling and Heating due to Climate Change)[42]

This work then applies a damage function for calculating additional energy consumption for cooling and heating due to climate change. The damage function from the FUND model is integrated into the global CGE model. X denotes additional expenditure on space heating and cooling, a is the parameter for the impact of climate change on heating and cooling expenditure, ϵ_h is the parameter for the impact of economic growth on demand for heating, ϵ_c is the parameter for the impact of economic growth on demand for cooling, $cumAEEI_{t,r}^{1990}$ is the cumulative value of AEEI since 1990, and γ is parameter for the impact of the global temperature changes on cooling expenditures.[43]

$$X_{t,r}^{heating} = a_r^{heating} Y_{1990,r} \left(\frac{\operatorname{atan}(Temp_{t,r} - Temp_{1990,r})}{\operatorname{atan} 1.0}\right)\left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\epsilon_h}\left(\frac{pop_{t,r}}{pop_{1990,r}}\right)/cumAEEI_{t,r}^{1990}$$

Equation (8)

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

Equation (9)

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

We can thus see that the global CGE model has a structure that calculates global mean temperature changes from the climate module and then determines additional energy consumption for cooling and heating due to temperature change. This additional expenditure comes back to the global CGE model and affects production and equilibrium. Accordingly, it affects global greenhouse gas emissions and temperature changes.

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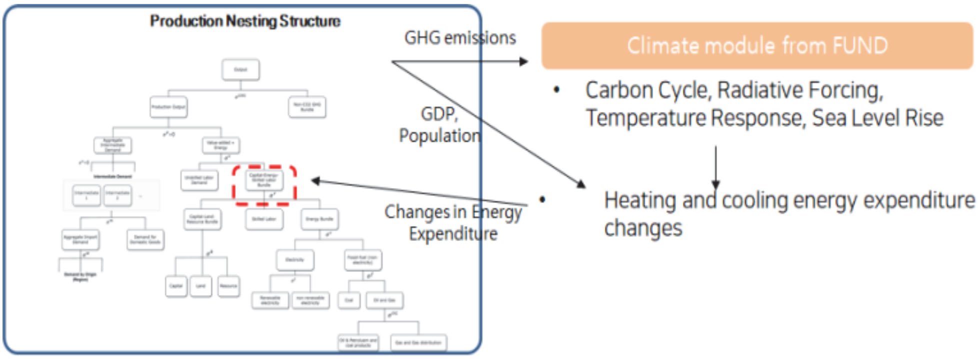
[42] The damage function "Energy Consumption" in MimiFUND (July 14, 2020) is considered.

[43] MimiFUND (July 14, 2020), "MimiFUND", accessed on May 17, 2023.

Figure 29. Integration of the climate module and the damage function of the FUND Model into the global CGE model



Source: The authors.

To integrate changes in energy consumption for cooling and heating, the study first calculates the total amount of energy-related bundles (TQENL), which aggregate QENL (aggregate energy bundle) and electricity and energy input consumption of households.

$$TQENL_r = \sum_{i,v} QENL_{r,i,v} + \sum_{i \in ely} QC_{r,i} + \sum_{i \in e} QC_{r,i} \qquad \text{Equation (10)}$$

The study then determines the relative scale of additional expenditure on cooling and heating compared to the total amount of energy-related bundles. To include such impacts, the study adjusts the share parameter of the KTRE bundle, which is the aggregate of the energy-capital-skilled labor bundle. The share parameter of the energy bundle in the KTRE bundle is adjusted accordingly, and to make the sum of all share parameters equal to one, the changes are adjusted by the share of skilled-labor bundle in the KTRE bundle. That is, the additional expenditure for cooling and heating sacrifices the expenditure on skilled-labor.

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

Equation (11)

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

Equation (12)

3.4 Constraints on Household Energy Consumption (Electricity and Other Energy Sources)

Based on the results of our survey of the relevant literature, we can see that low energy demand scenarios require components that alter individuals' consumption behaviors. Required behavioral changes include limiting excess consumption, altering energy-consuming habits, and adopting a new, less energy-intensive lifestyle. There is, however, very limited evidence on the potential of those behavioral changes to achieve reductions in energy consumption, particularly at the aggregate level. The demand analysis has been largely conducted at the individual or community levels, or for single or small bundles of actions. Applying these changes to a global CGE model is extremely difficult, so this study considers such changes as exogenous shocks.

There is no clear-cut way to reflect these changes, so changes in demand are often reflected by changing the elasticities of CES functions. However, it is difficult to reflect altered preferences as discussed in LED scenarios. To do so over time, in this study, we chose to gradually shift the share parameter, referencing Chepeliev et al. (2022, pp.6-11) and van der Mensbrugghe (2024, pp.66-69). To reflect changes in consumer preferences, those studies applied a so-called "phantom tax" to produce targeted reductions. Also, to incorporate a concept termed 'redesign,' those studies reduced intermediate use of materials and increases in other types of consumption. For this study, the method by which the above-mentioned works adjusted the share parameter to apply the "redesign" concept in the production process of the circular economy is applied to household consumption (Chepeliev et al., 2022, pp.10). We do this instead of applying a phantom tax to eliminate the need to consider specific targets or pathways for changes in energy demand.

Given constraints on household energy consumption, the share parameter of energy (that is, the electricity and energy bundle) shrinks by a pre-specified rate (1.25% per year for the Global South and 1.5% per year for Global North). $RatioCR_t$ denotes consumption constraints at time t. The sum of all changes in all share parameters of energy sources is redistributed proportionally to other, non-energy sectors. This indicates that the share of expenditure of energy commodities will decrease, and the share of spending on other commodities will increase.

$$A\_CCH_{r,i} = A\_CCH0_{r,i} \times RatioCR_t \qquad \text{Equation (13)}$$

4 Development of the Low Energy Demand Scenario

4.1 Summary of the Low Energy Demand Literature

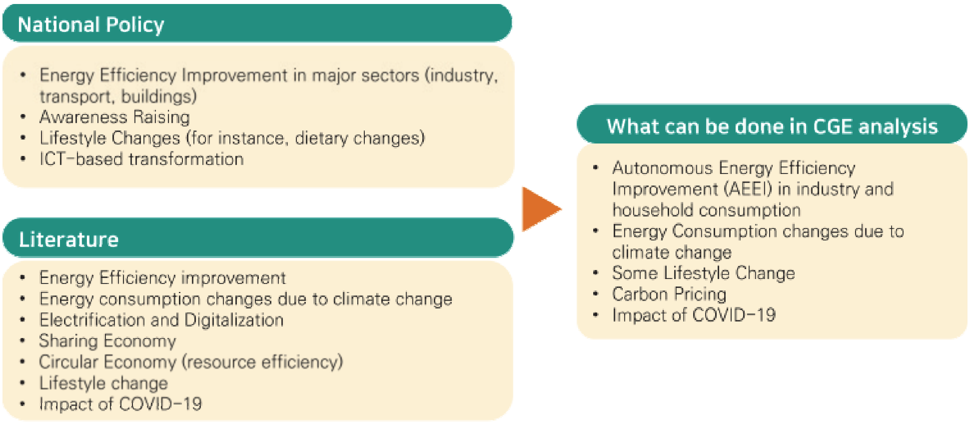
An increasing number of studies are focusing on the energy demand side, and the regional and sectoral scopes vary significantly. Demand-side approaches include a wide range of measures, from altering energy-consuming behavior to installing innovative technologies in the industrial sector. However, there are a limited number of quantitative analyses, and only a few modeling analyses are available. Even in modeling analysis, integrated assessment models or bottom-up models are largely utilized to analyze demand-side approaches. The CGE model can assess the economy-wide impacts of demand changes, but it is aggregated, and thus, difficult to incorporate such demand-side measures into the model. Therefore, this analysis considered a few concepts to establish the narrative of the low energy demand scenario and incorporates these aspects into the CGE model exogenously.

Based on the literature and countries' policies, 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. Thus, it is necessary to understand the economic impact of these efforts in the context of a net-zero transition.

From a review of the national policies of Korea, the EU, and Germany, this study found that the key policy instruments for encouraging energy demand reduction focus on energy efficiency improvement in major sectors (industry, transport, and buildings), raising public awareness, facilitating lifestyle change (i.e, dietary change, encouraging public transport), and promoting ICT-based transformation.

Similarly, the literature also emphasizes key instruments, such as energy efficiency improvement and lifestyle change. Additionally, many studies have assessed energy consumption changes due to climate change, electrification and digitalization, sharing and circular economies, and the impact of COVID-19.

Figure 30. Energy demand components considered in the CGE analysis, based on the 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

Source: The authors.

Based on the literature review, key policy instruments and components of energy consumption changes were identified. The global CGE model is largely an aggregated model; thus, all detailed interventions and policy measures cannot be properly integrated. Considering the structure of the global CGE model in this study, these measures were integrated through autonomous energy efficiency improvements in industry and households (energy efficiency), the damage function for energy consumption changes due to climate change, exogenous assumptions on energy consumption reductions in households (lifestyle change), future carbon pricing, and the application of the updated SSP scenario with the impact of COVID-19.

4.2 Structure of the Low Energy Demand Scenario

Based on the literature review, this study applies a scenario in which the key factors affecting changes in energy demand are largely exogenous, with some determined endogenously within the model. The assumptions regarding energy efficiency improvements and changes in household energy consumption patterns that underlie the low energy demand scenarios in this study are mainly exogenous.

First, energy efficiency improvements based on the literature and policy directions were included. Measures for improving energy efficiency are commonly considered important policy tools for reducing energy demand. It is assumed that energy efficiency improvements will occur when a carbon tax is applied, as efforts to improve energy efficiency will be more aggressively pursued. Additionally, the extent of energy efficiency gains may vary by region, with efficiency gains in developing countries likely to be greater than those in developed countries where the efficiency level is already high. To reflect this, energy efficiency gains were assumed to increase at a rate of 1.5% per year in the Global South (developing world) and 1% per year in the Global North (developed world). In the case of the AEEI, MIT's EPPA model (Chen et al., 2022, pp.7-8) and ENVISAGE models (van der Mensbrugghe, 2019, pp.3-9) assume 1% by default.

To improve energy efficiency in the real world, it is necessary to develop the necessary technologies and invest in facilities and equipment; however, this aspect is not applied in the global CGE model. Therefore, exogenous assumptions of energy efficiency improvement are applied rather than endogenous efficiency improvements. Additionally, energy efficiency improvement varies considerably by region, sector, and period. It is difficult to assume energy efficiency improvement by region and sector; the level of improvement varies greatly depending on the period analyzed, and the rate may vary depending on factors such as financial development, policy support, and technological development. Instead of considering the 1% rate assumed by other global models, additional energy efficiency gains were assumed to occur in developing countries, thereby increasing the rate by 1.5%. Consequently, a slightly higher assumption was set to account for the fact that several studies (SE4ALL, 2013, pp. 169-181; Popkova and Sergi, 2021; Shah et al., 2024, pp.73-80) indicate that developing countries have relatively lower levels of energy efficiency today and have the potential to achieve significant efficiency gains depending on the development of new technologies, the potential for energy efficiency improvements, and effective policy support.

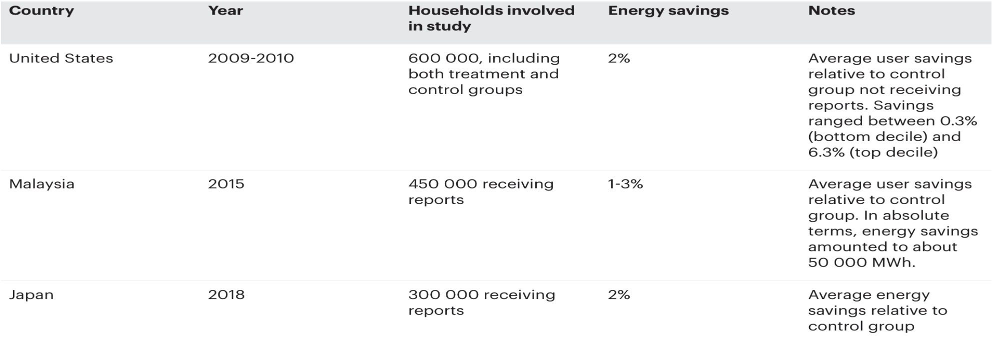
However, several studies have indicated the existence of rebound effects in energy efficiency gains. Besides energy efficiency improvement, this study includes other measures, such as carbon pricing, which could reduce rebound effects or even achieve negative rebound effects, as suggested by previous studies (Huang et al. 2023). However, the study's model does not include circular economy, dematerialization, and design shift, which are crucial for reducing energy and resource use in industry, due to insufficient evidence for making exogenous assumptions. Another limitation is that new industries such as hydrogen and CCS were not included. If a carbon price is applied, the revitalization of these new technologies and industries may impact the economy; however, this is not considered in the model used in this study.

Next, changes in heating and cooling energy consumption, including climate-induced consumption, were considered. This model includes the climate module and the damage function of heating and cooling energy consumption due to temperature change from the FUND model. It calculates the additional heating and cooling-related expenditure, and this will be included in the "KTRE" bundle. The heating and cooling energy demands are affected by the temperature change, and the impacts can vary by region. This can change the energy consumption landscape both regionally and globally.

Also, electrification with the further deployment of renewables was considered. Electrification may not unilaterally and directly reduce energy consumption, but electrification with a renewable energy transition suggests opportunities to reduce GHG emissions from fossil fuel consumption. In the NGFS Scenario analysis (NGFS, 2023, pp.23-39, pp.71-95), electrification through renewables was described as one of the components of the low demand scenario. In the global CGE model, it is challenging to include a selection of innovative technologies without a detailed bottom-up description of power technologies. Instead, this study applied the learning rate for renewables, which led to the rapid diffusion of renewable electricity. If carbon pricing is introduced, it is expected to replace fossil fuels faster, which will increase the utilization of renewable energy. Although this study does not directly reflect the electrification of each sector due to technological transitions, these assumptions are indirectly reflected in the acceleration of the transition from fossil fuels to renewable energy in each industry.

Then, exogenous constraints on household energy consumption (electricity and other energy sources) are introduced. Changing behavior is difficult to consider in the CGE model; therefore, the model assumes that each household reduces its energy consumption at a pre-determined rate every year. The low energy demand scenario considers behavioral changes in people and households, such as limiting excess consumption, altering energy-consuming habits, and adopting a new, less-energy-consuming lifestyle. The application of these changes to a global CGE model is limited and difficult. Therefore, this study considers such changes to be exogenous shocks. At the individual level, there have been studies on changes in energy consumption due to behavioral changes, but there are currently no studies that CGE models can analyze at the aggregate level. The IEA study(44) below analyzes how much energy consumption savings can be attributed to household behavior change through information and energy reporting and suggests energy savings of 2% between 2009 and 2010 in the US, 1-3% in Malaysia in 2015, and 2% in Japan in 2018. It also presents the level of energy consumption savings in the US through various behavioral change interventions, showing significant differences across interventions. The potential for behavioral changes to reduce energy consumption is still being explored.

Figure 31. The impacts of energy reports on energy savings



Country	Year	Households involved in study	Energy savings	Notes
United States	2009-2010	600 000, including both treatment and control groups	2%	Average user savings relative to control group not receiving reports. Savings ranged between 0.3% (bottom decile) and 6.3% (top decile)
Malaysia	2015	450 000 receiving reports	1-3%	Average user savings relative to control group. In absolute terms, energy savings amounted to about 50 000 MWh.
Japan	2018	300 000 receiving reports	2%	Average energy savings relative to control group

Source: IEA (June 4, 2021), “Impacts of Home Energy Reports across Selected Countries”, accessed on November 11, 2023.

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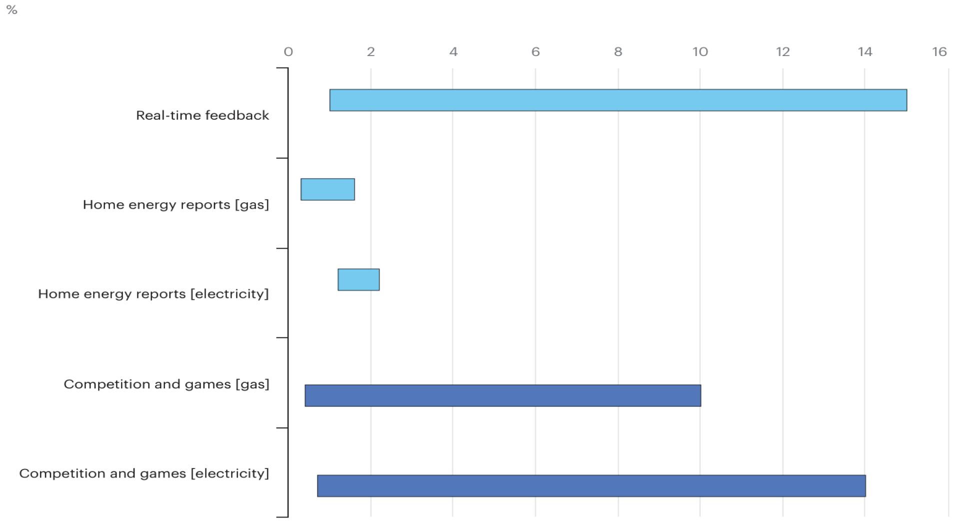
44) IEA (June 4, 2021), “The Potential of Behavioral Interventions for Optimizing Energy Use at Home”, accessed on November 11, 2023.

Figure 32. Energy savings from behavioral interventions in the United States



Source: IEA (June, 4, 2021), “Energy Savings across Behavioral Interventions Implemented in the United States”, accessed on November 11, 2023.

In particular, exogenous assumptions were applied because the current global CGE model can only reflect the aggregate level, whereas individual consumption behavior changes can be reflected in bottom-up and agent-based models, which include a very detailed representation of activities and technologies. Grubler et al. (2018) laid the foundation for the low energy demand narrative, and it can be seen that the changes in activities in consumer goods in the Global North can grow 79% (2020-2050) but the changes in energy demand can decrease by 25% (2020-2050). Therefore, there may be a relatively high consumption shift in energy sources to other commodities in the Global North. While there is no strong evidence or projection of changing the share of consumption composition by region, the study assumes that the annual reduction rates in energy consumption of 1.25% for the Global South and 1.5% for the Global North. This reduces the annual consumption share of electricity and energy sources by 1.25% and 1.5%, respectively, and allocates these amounts to other sectors. In sum, the study assumes that the energy efficiency improvement happens significantly in the Global South and the changing energy consumption behavior happens faster in the Global North.

In the Low Demand Scenario of the MESSAGEix model, by 2050, the "Final Energy|Residential and Commercial" is projected to decrease by an average of 2.1% per year in developed countries and 1.6% in developing countries, compared to the initial year 2020.[45] From the 12 regions of the MESSAGEix model, this study considers North America, the Pacific OECD, and Western Europe as the Global North and the other nine regions as the Global South. As explained in Chapter 5, when the low energy demand measures of industry and households are considered, the Global North and Global South will shrink by an average of 2.3% and 1.6% per year, respectively, from 2020 to 2050.

There are limitations to fully reflecting low energy demand measures in global CGE models owing to differences in structure, assumptions, and what can be included in each model. Additionally, CGE models have the issue that when the consumption of electricity and energy sources is reduced, the consumption of other commodities must be increased. Consuming more of a commodity with relatively low energy content can further reduce energy demand; however, energy demand reductions can also be smaller than expected when consuming more of a commodity with relatively high energy content. Instead of making assumptions about this, the sum of the changes in all share parameters of energy sources is redistributed proportionally to other non-energy sectors. This may cause the impact to vary across regions.

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45) Richters, Oliver et al. (November 7, 2023), "NGFS Climate Scenario Dataset (4.1)", accessed on November 15, 2023.

Figure 33. Impacts of LED scenarios on final energy demand in 2050

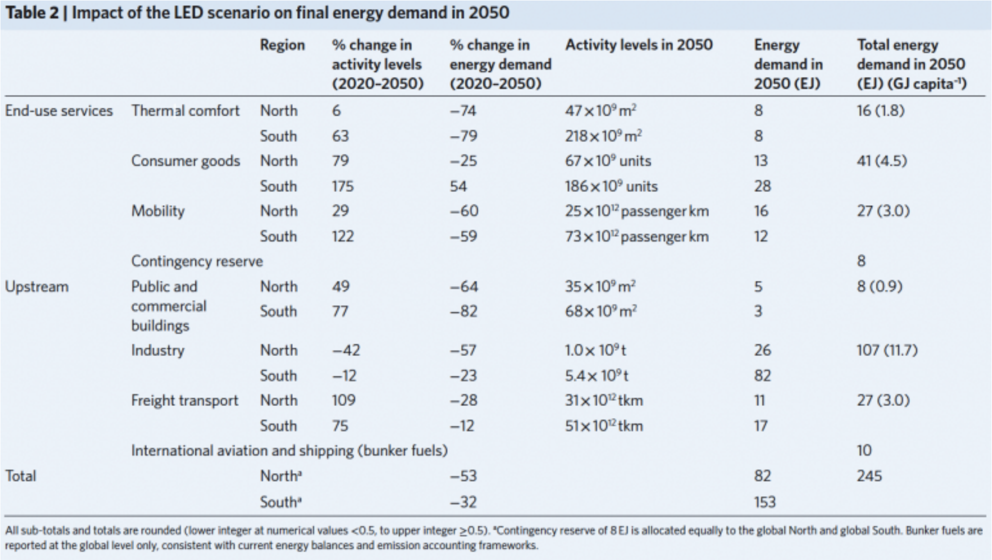

Table 2 | Impact of the LED scenario on final energy demand in 2050

		Region	% change in activity levels (2020–2050)	% change in energy demand (2020–2050)	Activity levels in 2050	Energy demand in 2050 (EJ)	Total energy demand in 2050 (EJ) (GJ capita^{-1})
End-use services	Thermal comfort	North	6	−74	47×10^{9} m^2	8	16 (1.8)
		South	63	−79	218×10^{9} m^2	8	
	Consumer goods	North	79	−25	67×10^{9} units	13	41 (4.5)
		South	175	54	186×10^{9} units	28	
	Mobility	North	29	−60	25×10^{12} passenger km	16	27 (3.0)
		South	122	−59	73×10^{12} passenger km	12	
	Contingency reserve						8
Upstream	Public and commercial buildings	North	49	−64	35×10^{9} m^2	5	8 (0.9)
		South	77	−82	68×10^{9} m^2	3	
	Industry	North	−42	−57	1.0×10^{9} t	26	107 (11.7)
		South	−12	−23	5.4×10^{9} t	82	
	Freight transport	North	109	−28	31×10^{12} tkm	11	27 (3.0)
		South	75	−12	51×10^{12} tkm	17	
	International aviation and shipping (bunker fuels)						10
Total		North[a]		−53		82	245
		South[a]		−32		153	

All sub-totals and totals are rounded (lower integer at numerical values <0.5, to upper integer ≥0.5). [a] Contingency reserve of 8 EJ is allocated equally to the global North and global South. Bunker fuels are reported at the global level only, consistent with current energy balances and emission accounting frameworks.

Source: Grubler et al. (2018), p.520.

Owing to a lack of relevant global databases and studies, the energy demand changes reflected in the scenario analysis in this study were based on several assumptions. Despite these limitations, the analysis of energy demand changes using a global CGE model with assumptions based on previous studies can contribute to understanding the potential of energy demand policies and measures to reduce GHG emissions.

To analyze the potential of low energy demand scenarios to achieve net zero, this study adopts an exogenous carbon pricing scenario. This study applied the NGFS Net Zero 2050 scenario. There are three carbon pricing pathways from the different Integrated Assessment Models (MESSAGEix-GLOBIOM, REMIND-MAgPIE, and GCAM). This study utilizes the carbon pricing pathways from the REMIND-MAgPIE because the REMIND model is a globally computable general equilibrium model.46)

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46) The study considered utilizing the results of the IIASA's MESSAGEix-GLOBIOM model, but that model focuses on energy systems analysis and employs a different modeling structure and scope of technologies than the global CGE model.

Table 11. Carbon prices used in Net Zero scenarios

(unit: USD)

	CPZ20	CPZ30	CPZ40	CPZ50
ANZ	22.2	155.9	539.6	790
SIS	9.2	97.8	300.2	526
EAS	5.5	105.2	354.7	645
JPK	16.6	155.9	436.8	610
KOR	16.6	155.9	436.8	610
SEA	5.5	85.9	285.1	538
SAS	2	48.8	220.4	526
CAN	22.2	155.9	539.6	790
USA	22.2	155.9	394.8	526
CAM	11.1	105.4	312.6	526
SAM	11.1	105.4	312.6	526
WEU	21.8	135.7	483.5	769
CEE	24.1	152.7	525.9	790
FSU	3.3	106.4	338	590
MDE	4.1	129.4	351.7	526
NAF	2.8	127	347.8	526
SSA	1.2	44.7	213.8	526

Note: The study utilized the NGFS Net Zero 2050 (REMIND-MAgPIE) Carbon Prices by Region and Year. In the case of the Republic of Korea, the study applied carbon prices identical to those used in Japan.

Source: Richters et al. (November 17, 2023), "NGFS Climate Scenario Dataset (4.1)", accessed on November 15, 2023.

The net zero carbon price in the REMIND-MAgPIE model varies greatly by region, with the Republic of Korea and the US having relatively low carbon prices in 2040 and 2050 compared with other regions (NGFS, 2023). The main reason for this is that the Republic of Korea is grouped in the Other Asia region in the REMIND model (Baumstark et al., 2021), and this region includes many Asian developing countries such as Afghanistan, Laos, and Thailand, resulting in a relatively low net-zero carbon price for the Republic of Korea. In the GCAM model with the Republic of Korea as a separate region, the 2050 carbon price in the net-zero 2050 scenario is USD 1,726.14/tCO_2 (in 2010 dollars), the highest in the world, compared to USD 1,187.19/tCO_2 in Japan, USD 1,226.92/tCO_2 in the United States, and USD 1,412.01/tCO_2 in Australia and New Zealand.[47] To reflect this situation, the carbon

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[47] Richter et al. (November 17, 2023), "NGFS Climate Scenario Dataset (4.1)", accessed on November 15, 2023.

prices in 2020, 2030, 2040, and 2050 in the NGFS scenario were mainly used for all regions except for the Republic of Korea, which applied the carbon price identical to that used in Japan. Additionally, the carbon price was set at a lower level than the 2020 carbon price before 2020 and then reached the CPZ20 carbon price in 2020. The carbon price was set to be fully implemented by 2021, and the carbon price pathway was set to increase gradually thereafter to reach CPZ30, CPZ40, and CPZ50. The model assumes a lump-sum approach to carbon revenue. In other words, revenue from carbon pricing is transferred to households.

Table 12. Description of scenarios

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 the Global North and 1.5% per year in the Global South
Net Zero Carbon Pricing (NZ)	- E_EXP scenario with Net Zero carbon pricing
Low Energy Demand in Industry with NZ (LED_ind_NZ)	- Follows NZ 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 the Global North and by 1.5% per year in the Global South
Low Energy Demand in Industry and Household with NZ (LED_all_NZ)	- Follows NZ scenario’s emissions pathways - In addition to the LED_ind_NZ 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 the Global South and the Global North, respectively

Source: The authors.

In the BAU scenario, economic and population growth follow the GDP and population projections from the updated SSP2 scenario from the EU NAVIGATE project. The carbon prices are assumed to rise to the 2020 carbon price in the NGFS scenario by 2020 but remain at 30% above the 2020 carbon price after 2020. The following Energy Expenditure (E_EXP) scenario follows the assumptions of the BAU scenario but reflects changes in cooling and heating energy consumption as temperatures rise. This scenario illustrates how the global economy and GHG emission projections will change when considering changes in cooling and heating energy consumption due to rising temperatures and GHG emissions by 2050. Next, the Low Energy Demand in Industry (LED_ind) scenario adds energy efficiency improvement to the E_EXP scenario. In the global CGE model, energy efficiency improvement is assumed to increase by 1% per year in the Global North and by 1.5% per year in the Global South, as described in the previous section. The focus is on energy efficiency, which has been emphasized in many studies and policies.

The next scenario involves carbon prices. The Net Zero Carbon Pricing (NZ) scenario was based on the NGFS Net Zero 2050 (REMIND-MAgPIE model) carbon price assumptions for 2030, 2040, and 2050.[48] This scenario represents what happens if a carbon price is applied while accounting for changes in energy demand owing to rising temperatures. In other words, the NZ scenario is an E_EXP scenario with net-zero carbon pricing. The following two scenarios reflect increased energy efficiency and reduced household energy consumption, which are important for low energy demand changes: First, the low energy demand in the industry with a net-zero (LED_ind_NZ) scenario assumes an increase in energy efficiency improvement of 1% per year for the Global North and 1.5% per year for the Global South, besides the NZ scenario. Finally, the low energy demand in industry and households with a net-zero (LED_all_NZ) scenario adds household energy consumption efficiency improvements of 1% per year for the Global North and 1.5% per year for the Global South, and energy consumption reductions, which are assumed to reduce household energy consumption by 1.25% per year in the Global South and 1.5% per year in the Global North. This scenario captures all the low energy demand measures explored in this study. In all the scenarios, a learning rate of 15% was applied to promote the diffusion of renewable energy. This can accelerate the adoption of renewables, which in turn accelerates electrification. With the introduction of the carbon pricing policy, the carbon price between the scenarios with and without the NZ carbon price will start to differ in 2022, and demand changes, such as energy efficiency, will start in 2024.

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[48] Richter et al. (November 7, 2023), “NGFS Climate Scenario Dataset (4.1)”, accessed on November 15, 2023.

These scenarios allowed us to explore various findings. First, this study analyzes the magnitude of the global temperature increase under different emission pathways and the impact of changes in energy demand as temperatures rise. This study analyzes the effects of energy efficiency improvements in the industrial sector. This is the effect of including only industrial energy efficiency improvement in the absence of carbon price and it can possibly analyze the existence and extent of the rebound effect of energy efficiency improvement. Next, this study examines the impact of energy efficiency improvements, the main instruments for reducing energy demand in the industry, and the impact of energy efficiency improvements and energy consumption reductions in households in the net-zero transition pathway. The net-zero carbon pricing scenario allows us to analyze the changes in emissions, economic impacts by country and sector, and the extent to which the global temperature rise can be limited under a carbon price. The economic impact of low energy demand measures in industry and households under carbon prices, as well as their potential to reduce the burden of GHG mitigation, is explored.

5 Results and Policy Implications

5.1 Results: LED Scenario Analysis

In this study, the global CGE model was applied to the six scenarios described earlier and was analyzed through to 2050. The advantage of the global CGE model is that it shows both domestic and global changes in response to changes in carbon prices and low energy demand measures. Therefore, the results of this study are presented separately for the global outcomes and domestic outcomes within the Republic of Korea.

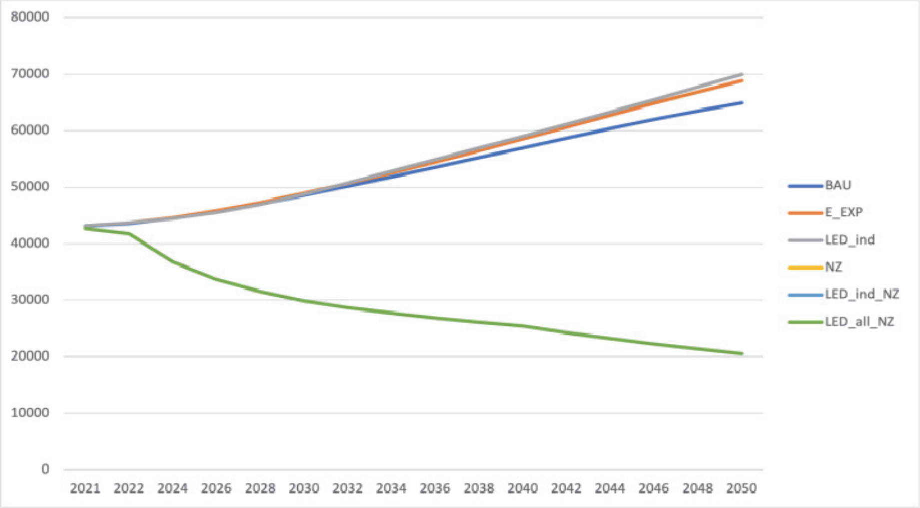
5.1.1 Global

For global GHG emissions, changes in cooling and heating energy demand due to climate change will increase global GHG emissions slightly. Global GHG emissions can decline rapidly with a net-zero carbon price. However, this model does not include negative emissions, such as DAC, CCS, or other low-carbon technologies to transition to net zero, such as hydrogen; therefore, emissions do not converge to zero and continue to persist.

As described earlier, the reduction and emission pathways relative to BAU are the same for the NZ, LED_ind_NZ, and LED_all_NZ scenarios, as the following industrial and household low energy demand measures are applied while keeping GHG emissions in the NZ scenario. The current model shows a global reduction of approximately 45% below the BAU model with carbon prices.

Figure 34. Global GHG emissions (2021-2050)

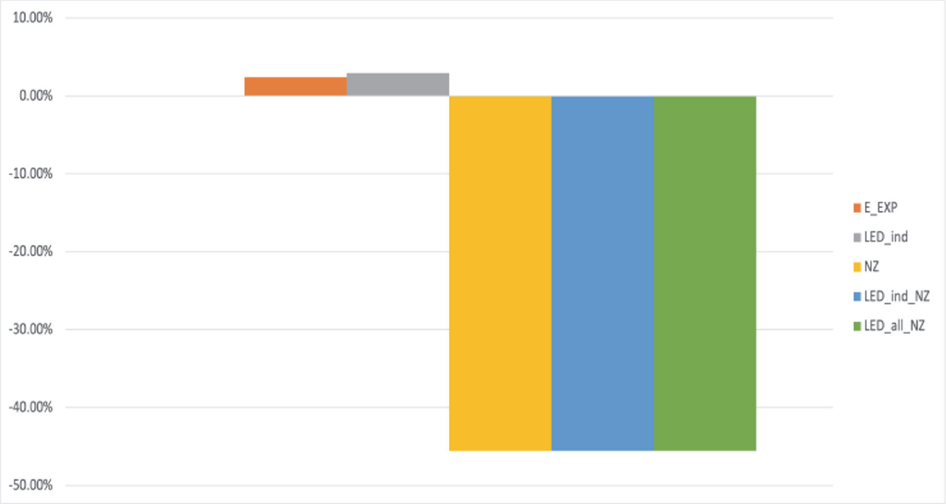
(unit: $MtCO_2eq$)



Note: The LED_ind_NZ and LED_all_NZ scenarios follow the emission pathway of the NZ scenario.
Source: The authors.

Figure 35. Changes in global GHG emissions (2021-2050) (relative to the BAU)

(unit: %)



Note: The LED_ind_NZ and LED_all_NZ scenarios follow the emission pathway of the NZ scenario.
Source: The authors.

The global mean temperature increase could go beyond 2℃ in the next few decades if there are no strict carbon pricing or mitigation measures. Additionally, climate change can increase global demand for cooling and heating energy, eventually increasing GHG emissions. Although the impact on global temperature change seems negligible, it can hinder global efforts to reduce GHG emissions and climate change. The result of the global mean temperature increase is similar to the results from other IAMs with SSP2 scenario. Based on the SSP2-Baseline scenario, the median surface temperature from global IAMs indicated around 2-degree in 2050.[49)][50)]

Additionally, the results suggest evidence of the rebound effects of energy efficiency improvement, similar to other CGE models (Huang et al., 2023). Energy efficiency improvement in industrial sectors (LED_ind) leads to an increase in final energy demand relative to the BAU level. These rebound effects result in a GHG increase of approximately 6.68% in 2050 relative to the BAU scenario. The results are similar to those from other CGE models reviewed in Huang et al. (2023), and if net-zero carbon pricing is applied, it is expected that the global temperature increase can be limited to slightly less than or almost 2℃ by 2050. Even without accounting for CCS, DAC, or carbon sinks, the results show that carbon prices can lead to significant GHG reductions and constrained temperature increases.

The following shows the changes in the final energy demand by scenario: Climate change leads to an increase in cooling and heating energy consumption, which in turn leads to an increase in final energy demand. Similarly, as mentioned earlier, energy efficiency improvements have a rebound effect, leading to an increase in final energy consumption relative to the BAU. Carbon pricing leads to significant reductions in final energy demand. The model shows a slight increase in final energy consumption relative to the BAU near 2040, which is due to an increase in the consumption of electricity from renewable sources. Near the year 2040 or mid-2040s, the changes in the final energy demand reached the bottom and started to increase gradually in the net-zero scenario compared to the BAU scenario. It

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49) IIASA (November 9, 2022), “AR6 Scenarios Database hosted by IIASA”, accessed on March 25, 2023.

50) The results indicate ‘Surface Temperature (GSAT), MAGICCv7.5.3, 50th Percentile’ under the SSP2-Baseline scenario from the global IAMs (AIM/CGE 2.0, GCAM 4.2, IMAGE3.2, MESSAGE-GLOBIOM 1.0, REMIND-MAgPIE 1.5, and WITCH-GLOBIOM 3.1).

showed significant reductions in fossil fuels (coal, oil, gas, and petroleum and coal products) but a substantial increase in renewable and nuclear electricity. This impact arises because the global CGE model in this study only reflects energy efficiency improvements in the industrial sector and does not reflect other energy and resource demand reduction policies and measures, such as dematerialization, feedstock switching, innovative technologies, and redesign.

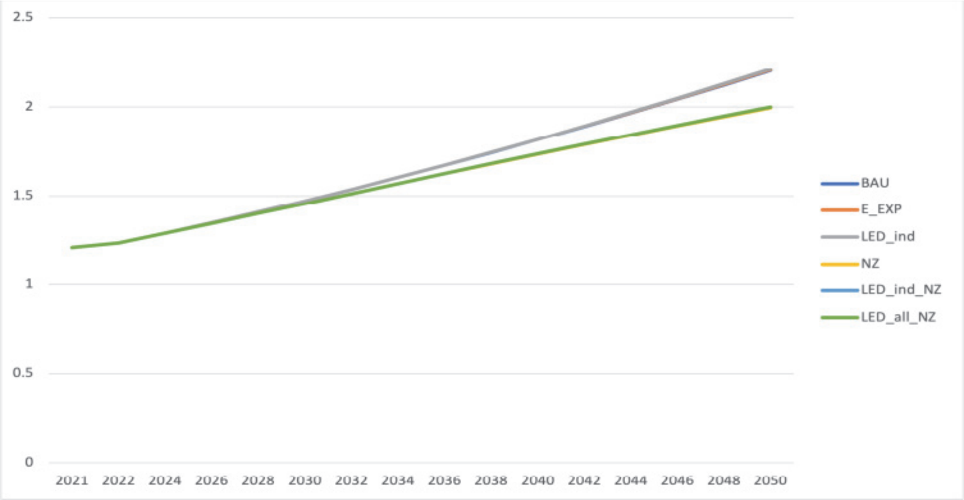
While the final energy demand increased when only energy efficiency improvements were included, with the combination of net-zero carbon pricing, energy efficiency improvements in all sectors could lead to a larger decrease in final energy demand and reach an approximately 30.1% reduction relative to the BAU level. Finally, the N improvements and energy consumption reduction measures were included.

In conclusion, energy efficiency improvements in industrial and household consumption, as well as household energy consumption reduction alone, would have limited effects on GHG emissions and energy demand reduction. However, the results indicate that energy efficiency improvements and energy consumption reductions could achieve greater energy demand reductions relative to the BAU scenario if sufficient carbon pricing is accompanied by these measures. Although additional industrial energy efficiency improvements can contribute to major final energy demand reductions relative to the net-zero carbon pricing scenario, household energy efficiency improvements and energy consumption reductions can also contribute to additional energy consumption reductions.

Introducing innovative technologies such as hydrogen, DAC, and CCS, which are not considered in this model, could further reduce or remove GHG emissions. It could lead to limiting the global temperature increase to below the 2℃ target.

Figure 36. Global temperature change above pre-industrial levels

(unit: ℃ above pre-industrial levels)

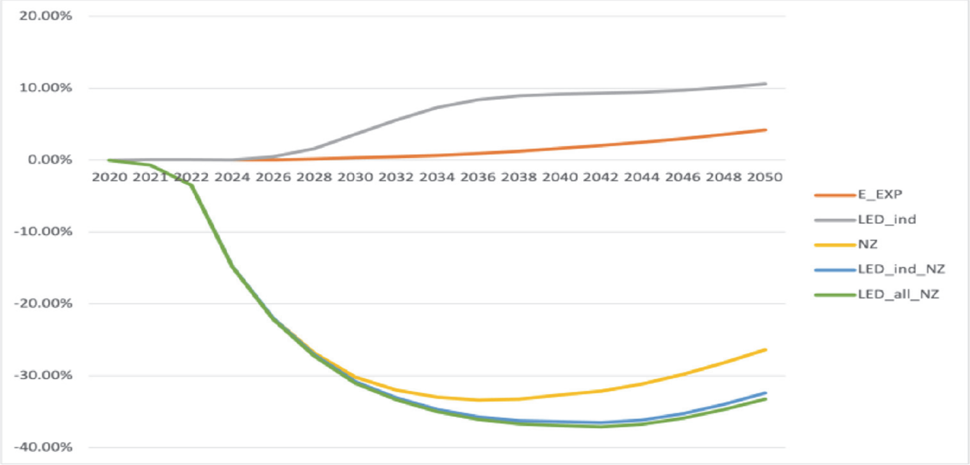


Note: The LED_ind_NZ and LED_all_NZ scenarios follow the emission pathway of the NZ scenario. Thus, global temperature change remains the same in the NZ, LED_ind_NZ, and LED_all_NZ scenarios.

Source: The authors.

Figure 37. Changes in global final energy demand by scenario (relative to BAU)

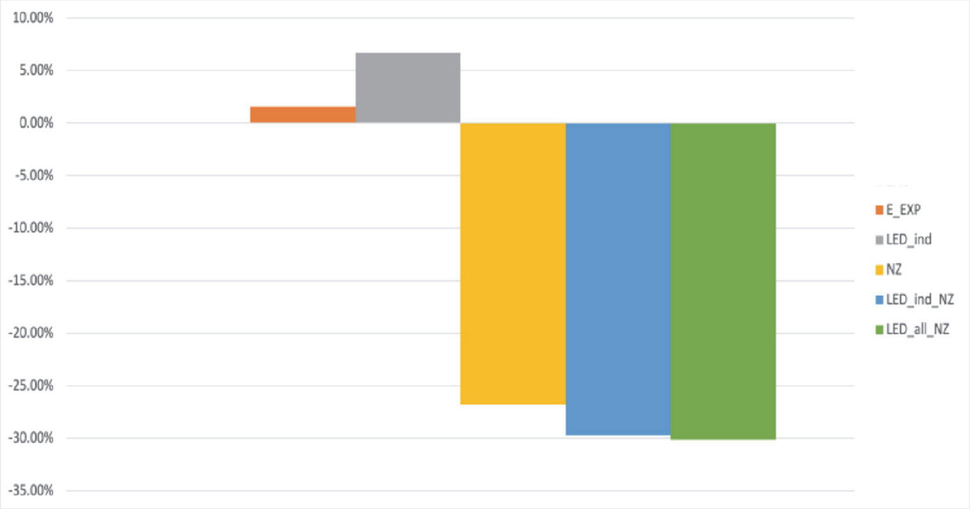
(unit: %)



Source: The authors.

Figure 38. Changes in global final energy demand (2021-2050) by scenario (relative to BAU)

(unit: %)



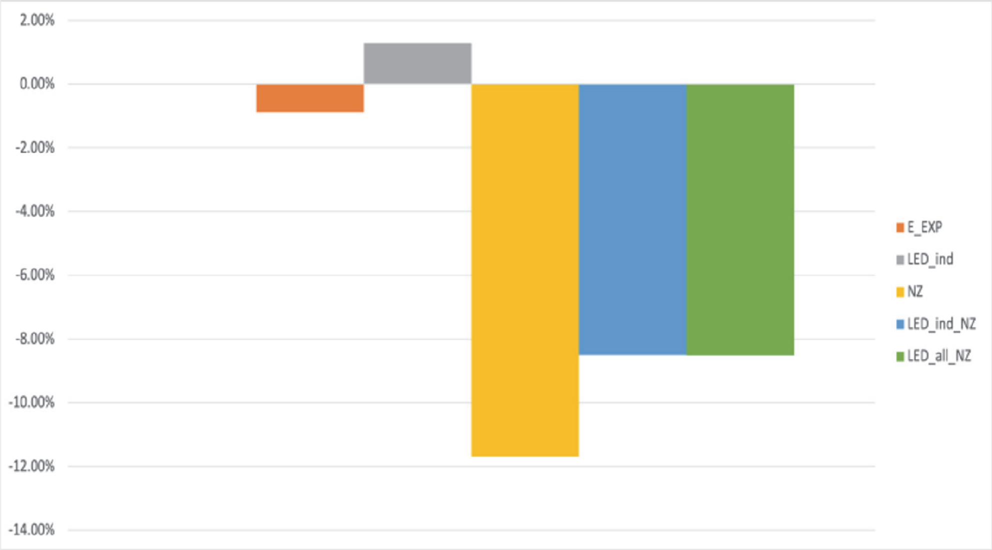
Source: The authors.

For economic impacts, the introduction of carbon pricing leads to some economic losses globally, and low energy demand measures, besides carbon pricing, could reduce the negative economic impacts compared with the NZ scenario. Under the NZ scenario, global GDP would be reduced by approximately 11.7% compared to the BAU over the 2021–2050 period. However, energy efficiency improvements in industry and households and reduced household energy consumption have the potential to reduce this economic impact by approximately 8.5%. In other words, low energy demand measures can reduce the economic burden of achieving a net-zero transition.

At the regional level, the results indicate that the economic impacts vary considerably by country. Currently, the global CGE model applies the NGFS Phase 4 scenario carbon prices from the REMIND-MAgPIE model, and the results show that developing economies generally experience larger declines than developed economies relative to BAU. A possible explanation is that the NGFS carbon prices suggest that by 2050, carbon prices in developing countries will align with those in developed countries and these nations will achieve Net Zero. Although regional economic impacts vary significantly, low energy demand measures reduce the economic burden in all regions. Although the magnitude of the benefits varies, improving energy efficiency and reducing household energy consumption have positive economic outcomes. The Republic of Korea appears to have a relatively lower economic impact than the other regions. This is similar to the results of studies by Li and Duan (2020) and Xiaobei, Fan, and Jun (2022, pp.6-11), who found that the economic impacts of GHG reductions and carbon pricing, such as achieving NDCs, in Korea, are relatively low or similar to those in other developed regions.

Figure 39. Changes in global real GDP (2021-2050) (relative to BAU)

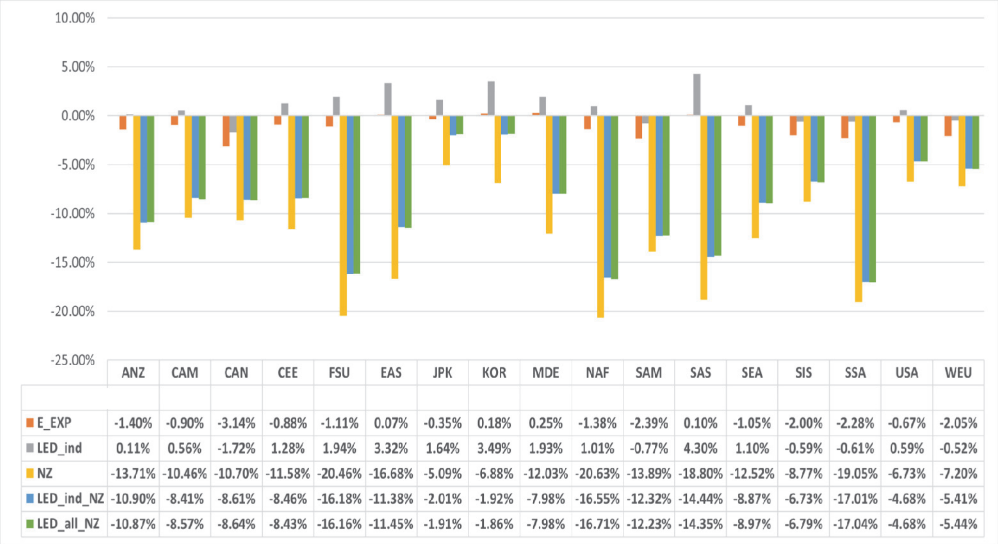
(unit: %)



Source: The authors.

Figure 40. Changes in regional real GDP (2021-2050) (relative to BAU)

(unit: %)



	ANZ	CAM	CAN	CEE	FSU	EAS	JPK	KOR	MDE	NAF	SAM	SAS	SEA	SIS	SSA	USA	WEU
■ E_EXP	-1.40%	-0.90%	-3.14%	-0.88%	-1.11%	0.07%	-0.35%	0.18%	0.25%	-1.38%	-2.39%	0.10%	-1.05%	-2.00%	-2.28%	-0.67%	-2.05%
■ LED_ind	0.11%	0.56%	-1.72%	1.28%	1.94%	3.32%	1.64%	3.49%	1.93%	1.01%	-0.77%	4.30%	1.10%	-0.59%	-0.61%	0.59%	-0.52%
■ NZ	-13.71%	-10.46%	-10.70%	-11.58%	-20.46%	-16.68%	-5.09%	-6.88%	-12.03%	-20.63%	-13.89%	-18.80%	-12.52%	-8.77%	-19.05%	-6.73%	-7.20%
■ LED_ind_NZ	-10.90%	-8.41%	-8.61%	-8.46%	-16.18%	-11.38%	-2.01%	-1.92%	-7.98%	-16.55%	-12.32%	-14.44%	-8.87%	-6.73%	-17.01%	-4.68%	-5.41%
■ LED_all_NZ	-10.87%	-8.57%	-8.64%	-8.43%	-16.16%	-11.45%	-1.91%	-1.86%	-7.98%	-16.71%	-12.23%	-14.35%	-8.97%	-6.79%	-17.04%	-4.68%	-5.44%

Source: The authors.

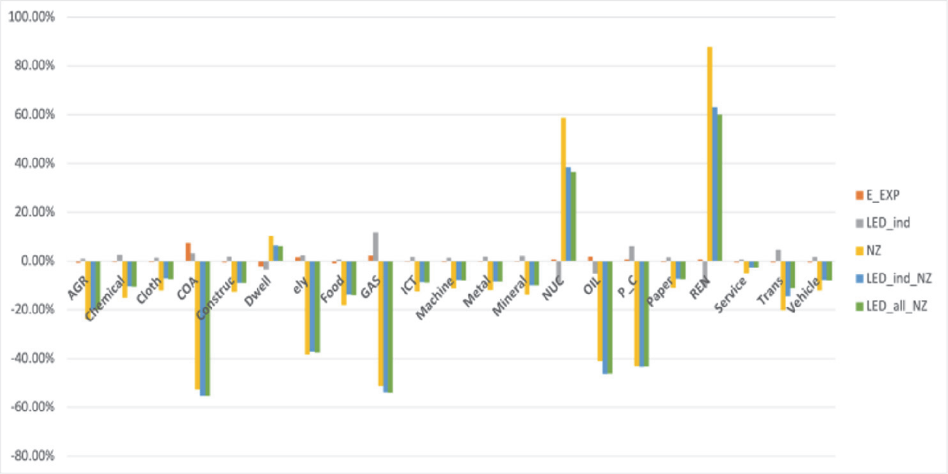
Net-zero carbon pricing can reduce global production and investment in several sectors. In particular, global production and investment in fossil fuels and non-renewable electricity decrease significantly when net-zero carbon pricing is implemented. However, there have been significant increases in investments and production in the renewable and nuclear power sectors. This indicates a shift occurs from fossil fuels to renewable or nuclear power when carbon pricing is applied.

Overall, production and investment exhibited similar patterns. The introduction of demand-side measures, besides carbon prices, appears to reduce the negative impact on production and investment (relative to the BAU level) in many non-energy sectors. This means that energy demand policies, such as energy efficiency improvements and behavioral changes to reduce household energy consumption, can reduce GHG emissions while lowering the negative economic impacts of mitigation actions.

Implementing carbon pricing is expected to result in significant changes across industries. In particular, the transition of energy-related industries could have a significant impact on GHG emission reduction. Fossil-fuel-related industries, such as the coal and gas sectors, are expected to decline by 38.3% to 58.8% over the 2021–2050 period compared with the BAU, and the potential for stranded assets and job losses can be substantial. Such a large change is likely to bring about discussions on Just Transition and emphasize the need for policy support to facilitate the transition.

Figure 41. Changes in global production by sector (2021–2050) (relative to BAU)

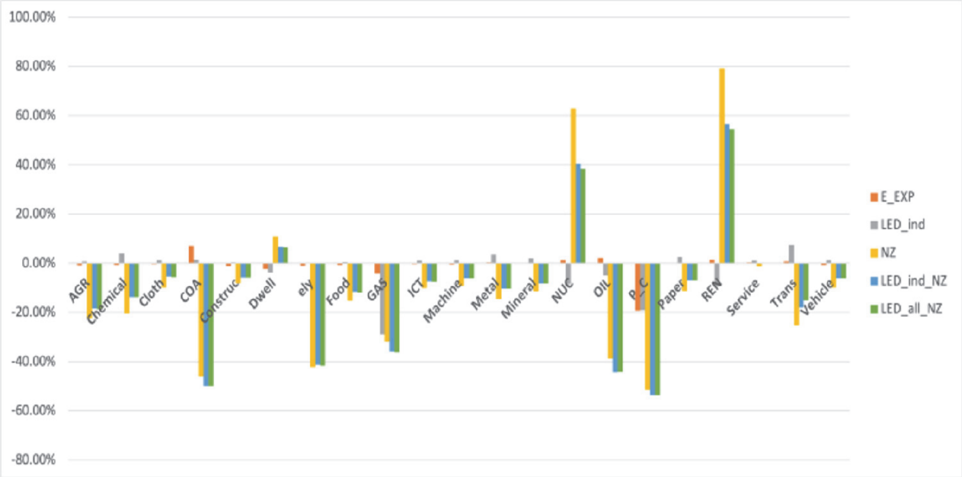
(unit: %)



Source: The authors.

Figure 42. Changes in global investment by sector (2021-2050) (relative to BAU)

(unit: %)



Source: The authors.

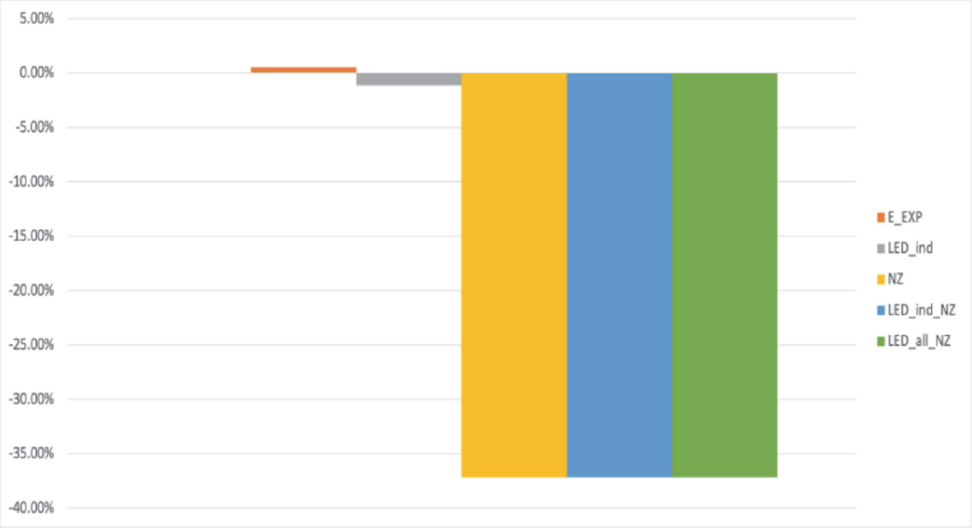
5.1.2 Korea

Similar to the global results, low energy demand measures such as energy efficiency increases and household consumption reductions in energy sources could slightly reduce GHG emissions in Korea. Although rising temperatures increase cooling and heating energy demands, the resulting increase in GHG emissions is expected to be minimal. In contrast to the global results, energy efficiency improvements have been shown to help reduce GHG emissions domestically.

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 NZ scenario by 2050. The NZ Scenario projects USD 610 per tCO_2eq in 2050, but the LED_all_NZ Scenario forecasts a price of USD 480 per tCO_2eq in 2050. This indicates the potential of demand-side measures to lower the carbon prices required to achieve the same level of GHG emission reduction. This implies the importance of policy measures for reducing the energy demand of industrial sectors, reducing GHG emissions, and meeting national mitigation targets.

Figure 43. Changes in Korea's GHG emissions (2021-2050) (relative to BAU)

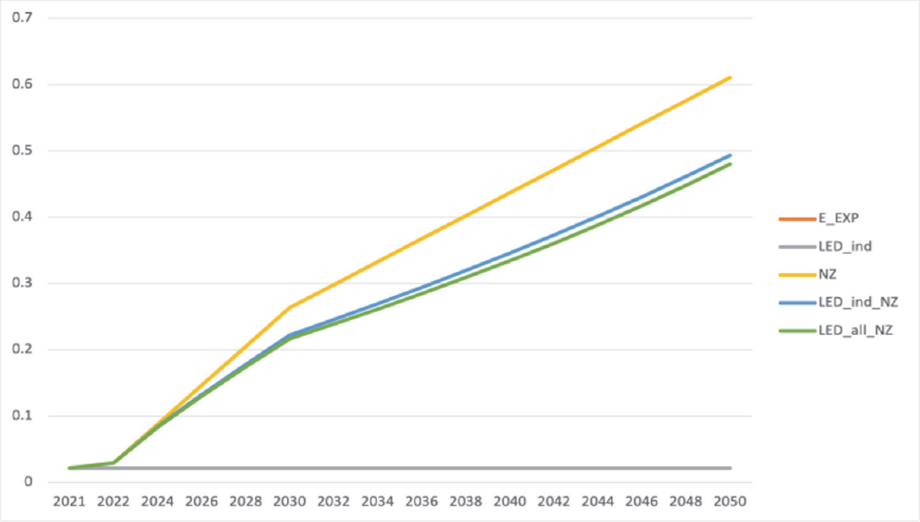
(unit: %)



Note: The LED_ind_NZ and LED_all_NZ scenarios follow the emission pathway of the NZ scenario.
Source: The authors.

Figure 44. Korea's carbon price trajectories by scenario (2021-2050)

(unit: USD 1,000)

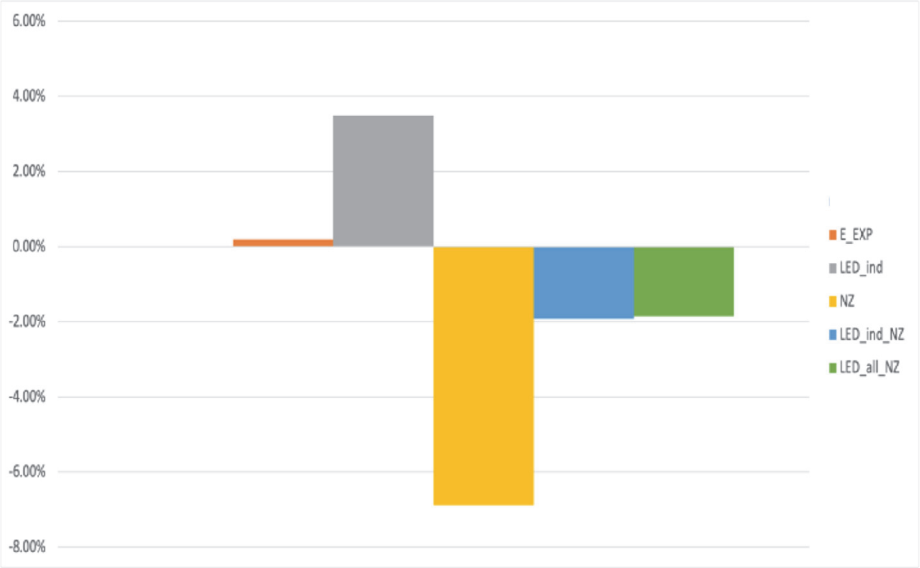


Source: The authors.

The net-zero transition (NZ Scenario) could lead to slight losses in real GDP (2021–2050), resulting in a decline of approximately 6.88% compared with BAU. However, if low energy demand measures are applied, GDP losses are significantly reduced. With improved energy efficiency in the industry, GDP losses are 1.92% of BAU, which is significantly lower than 6.88% in the NZ scenario. When household energy efficiency improvements and energy consumption reductions are included, economic losses can be reduced by 1.86% relative to the BAU. This indicates that policies or responses to industrial energy demand, such as improving energy efficiency in the industry, are important, although household efforts are also required.

Figure 45. Changes in Korea's real GDP (2021–2050) (relative to BAU)

(unit: %)



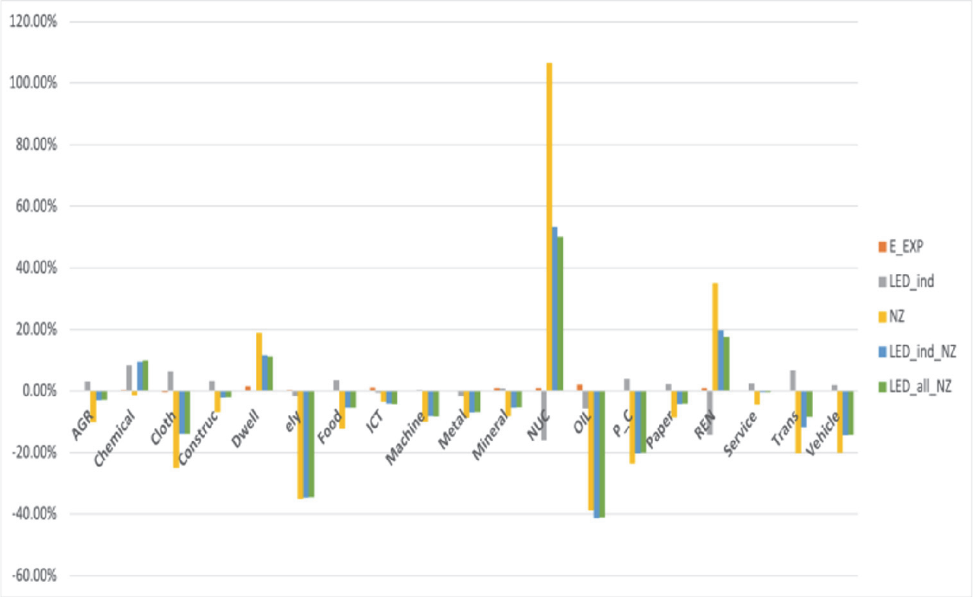
Source: The authors.

The production trends are similar to those in the global scenario. For sectoral production, net-zero carbon pricing would significantly increase the production of renewable and nuclear electricity, while decreasing fossil fuel-related production.

A distinctive characteristic of the results for the Republic of Korea is that there is a relatively substantial increase in nuclear power production compared to renewables. Although global production has seen a significant increase in renewables compared with the BAU, such an increase occurs in nuclear electricity production. There was a significant increase in renewable electricity, but this was smaller than that of nuclear electricity. Investment showed a pattern similar to that of production. Low energy demand measures with net-zero carbon pricing can reduce production and investment losses in non-energy-related sectors.

Figure 46. Changes in Korea's production by sector (2021-2050) (relative to BAU)

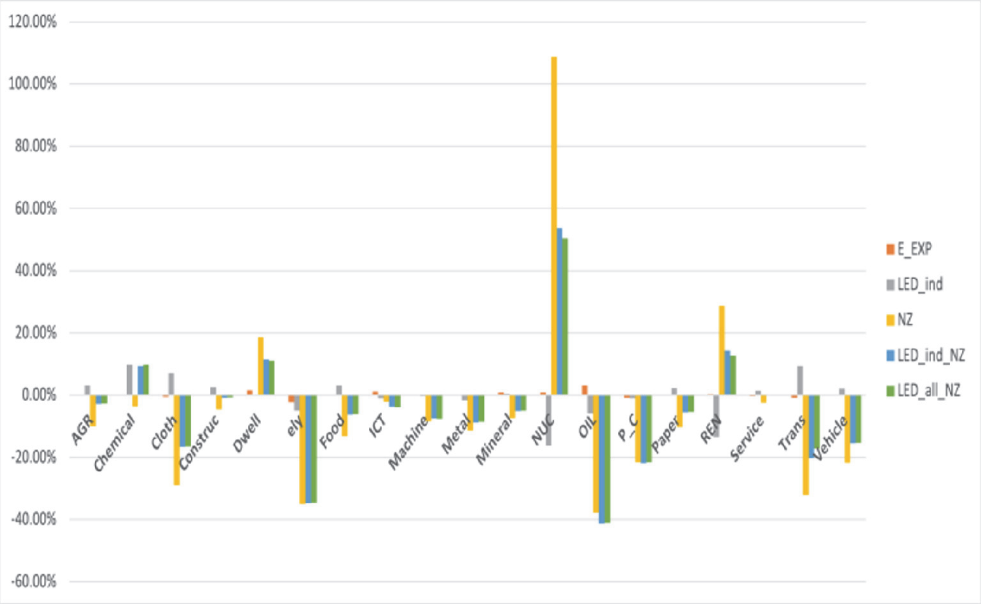
(unit: %)



Source: The authors.

Figure 47. Changes in Korea's investment by sector (2021-2050) (relative to BAU)

(unit: %)



Source: The authors.

5.2 Accelerated LED Scenarios

In this section, the study constructed an Accelerated Action scenario to explore the effects of taking accelerated demand-side approaches. The Accelerated Low Energy Demand Scenario (ACC_LED_NZ) is a scenario with a faster pace of energy efficiency improvements in industry and households, and a faster pace of household energy consumption reductions. The rate of the energy efficiency improvement is increased to 1.5% instead of 1% in the Global North and to 1.75% instead of 1.5% in the Global South, and household energy consumption reductions are accelerated to 1.5% per year in the Global South and 1.75% per year in the Global North. In this scenario, countries make greater commitments to promote energy efficiency and energy demand measures. Subsequently, an Accelerated but Delayed Low Energy Demand Scenario (ACC_delayed_LED_NZ) was constructed. This scenario follows the existing LED_all_NZ scenario until 2035, but with an accelerated rate of energy efficiency improvement and energy consumption reduction after 2035. This scenario considers 2035 as the time for accelerating demand-side approaches, as 2035 is the target year for the next global NDC submissions in 2025. This scenario represents an increased focus on the demand side after the next NDC target year.

Table 13. Description of the Accelerated LED Scenario

Scenario	Description
Accelerated Low Energy Demand Scenario (ACC_LED_NZ)	Accelerated efforts for energy efficiency improvements (industrial and household sectors) and energy consumption reductions (household sector) Accelerated energy efficiency improvements by 1.5% in Global North and 1.75% in Global South per year Accelerated household energy consumption reductions by 1.5% in the Global South and 1.75% in the Global North per year
Accelerated but Delayed Low Energy Demand Scenario (ACC_delayed_LED_NZ)	The assumptions of the ACC_LED_NZ Scenario apply to this scenario, but the accelerated actions happen after 2035 Until 2035, this scenario follows LED_all_NZ Scenario

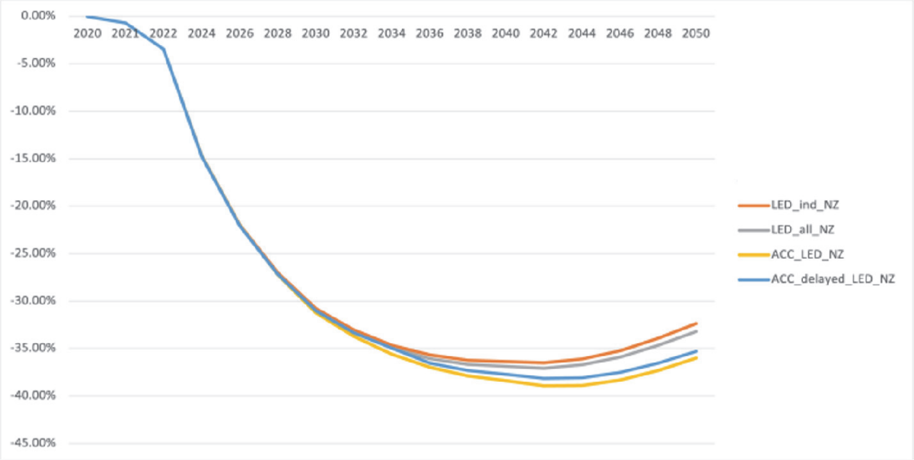
Source: The authors.

5.2.1 Global

Accelerated actions could further reduce the final energy demand and slow the pace of the increase in energy consumption after reaching a minimum in the mid-2040s. Additionally, accelerated actions could achieve more energy demand reductions relative to the BAU, although the level of energy demand reduction that could be achieved was not as dramatic. This is because there has already been a significant transition to electricity, particularly renewables, and the global CGE model does not reflect innovative technologies or measures that constrain demand in energy-consuming sectors. Therefore, the magnitude of the change may not have been significant.

Figure 48. Changes in global final energy demand by scenario (accelerated) (relative to BAU)

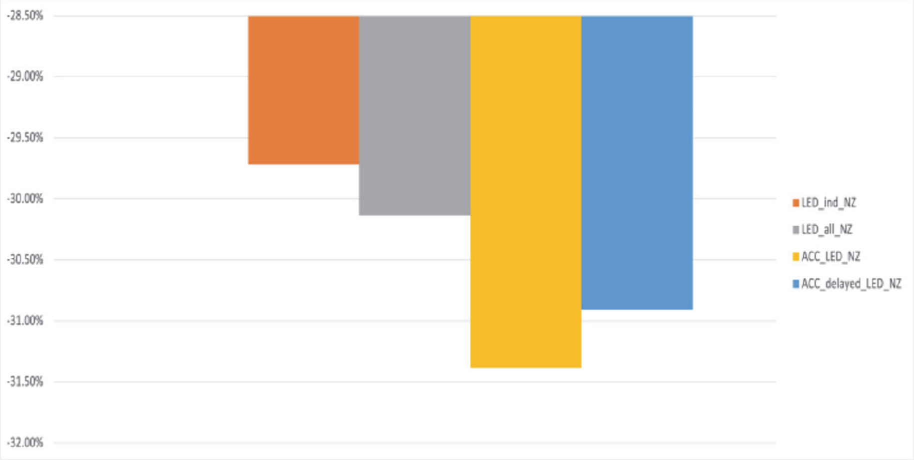
(Unit: %)



Source: The authors.

Figure 49. Changes in global final energy demand (2021-2050) by scenario (accelerated) (relative to BAU)

(Unit: %)

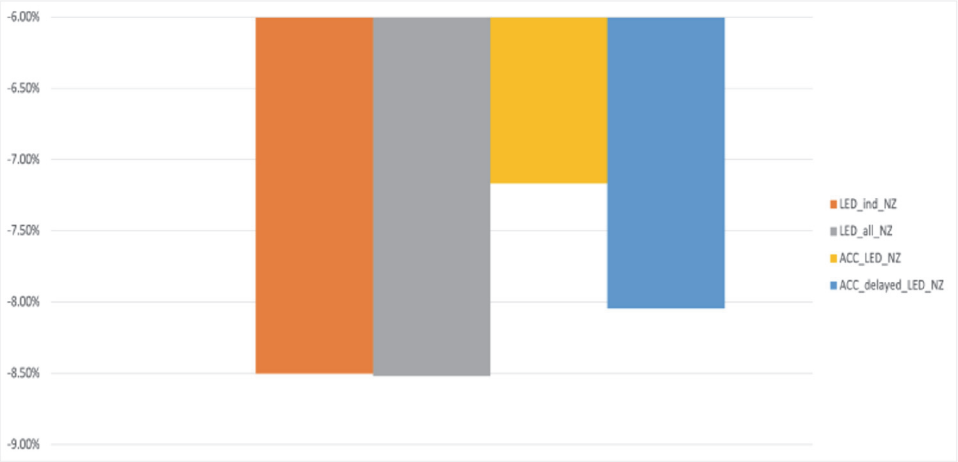


Source: The authors.

Accelerated but delayed action could also slightly reduce global real GDP losses in the Net Zero transition, and accelerated actions with increased energy efficiency and further reductions in household energy consumption could reduce global economic losses in the net zero transition. The GDP loss of the Accelerated Action is significantly reduced compared with the conventional low energy demand scenarios (LED_ind_NZ and LED_all_NZ). In the LED_all_NZ scenario, the GDP loss was 8.52% relative to BAU over the 2021–2050 period; with Accelerated Action, it significantly reduced to 7.17% relative to BAU. The accelerated but delayed action can reduce global GDP losses to 8.04% relative to BAU (2021-2050). The results indicate that countries can reduce economic costs while maintaining the level of GHG reduction if they increase their focus on demand, improve efficiency, and reduce household energy demand.

Figure 50. Changes in global real GDP (2021-2050) by scenario (accelerated) (relative to BAU)

(Unit: %)

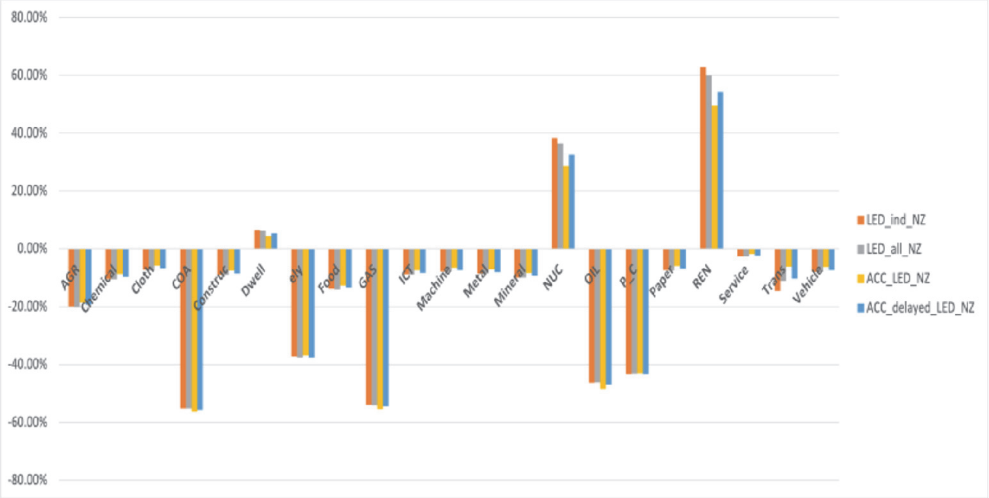


Source: The authors.

The general trends of global production and investment in the accelerated scenarios were similar to those of the net zero with low energy demand measures. It shows a significant decline in fossil fuel production and investment and a significant increase in nuclear and renewable electricity. The other non-energy sectors showed a slight decrease. The aggregate losses of global production and investment are reduced slightly under the accelerated scenarios compared to the net zero with low energy demand measures.

Figure 51. Changes in global production by sector (2020-2050) (accelerated) (relative to BAU)

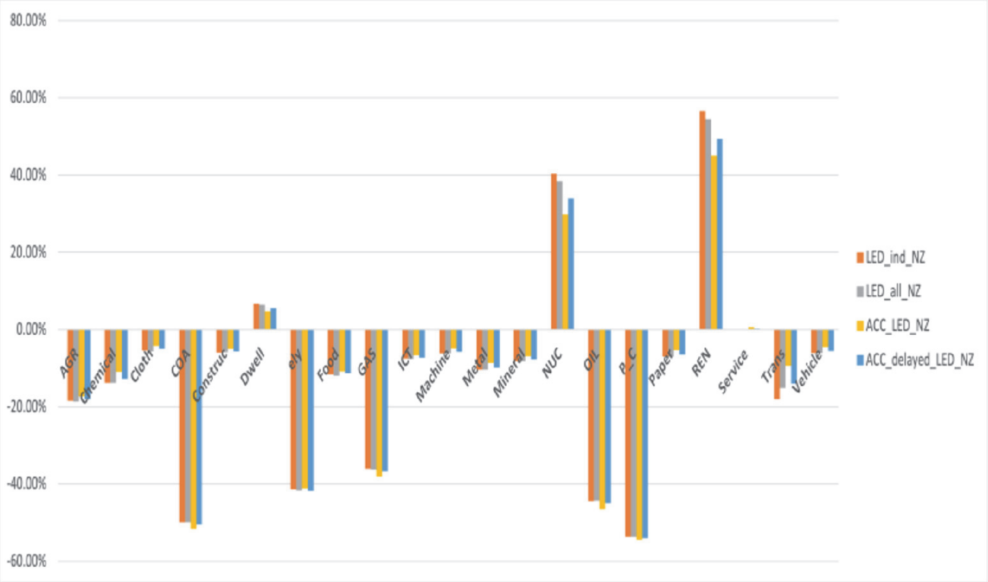
(Unit: %)



Source: The authors.

Figure 52. Changes in global investment by sector (2021-2050) (accelerated) (relative to BAU)

(Unit: %)



Source: The authors.

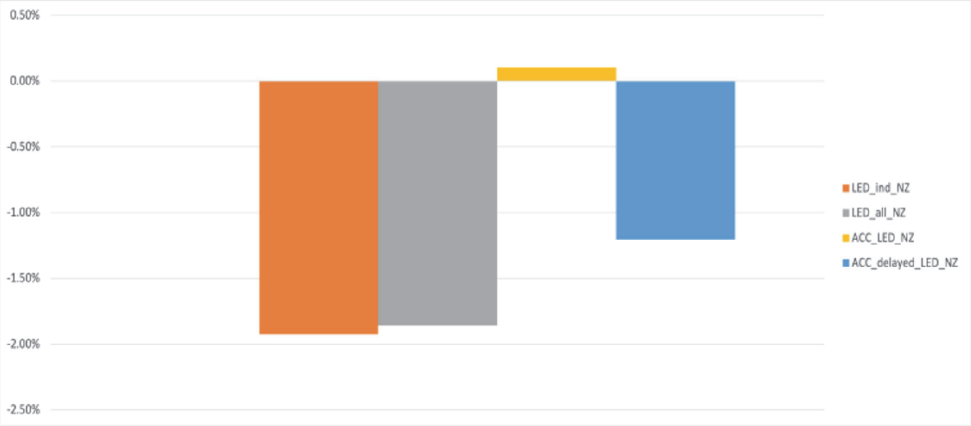
5.2.2 Korea

The results for the Republic of Korea were similar to the global results. However, accelerated actions could bring considerable economic gains to the Republic of Korea compared to the net zero with low energy demand measures. In particular, the changes in the GDP of the Republic of Korea are nearly equal to the BAU scenario in the accelerated LED scenario, while reducing GHG emissions suggests the potential of demand policies. Additionally, the carbon prices required to follow the net-zero emissions pathway become lower than the Net Zero scenario under the low energy demand measure scenarios. In particular, carbon prices in the accelerated scenarios were much lower than those in the net-zero scenario. In the previous section, the NZ scenario in 2050 was observed to project USD 610 per tCO_2eq, which is reduced to USD 480 per tCO_2eq in the LED_all_NZ scenario. In the accelerated LED scenario, the price is between USD 430 and USD 435 per

tCO_2eq, indicating that emission reductions can be achieved with lower carbon prices. This suggests that if stronger demand-related policies are implemented, the economic burden of GHG emissions reductions can be further reduced.

Figure 53. Changes in Korea's real GDP (2021-2050) (accelerated) (relative to BAU)

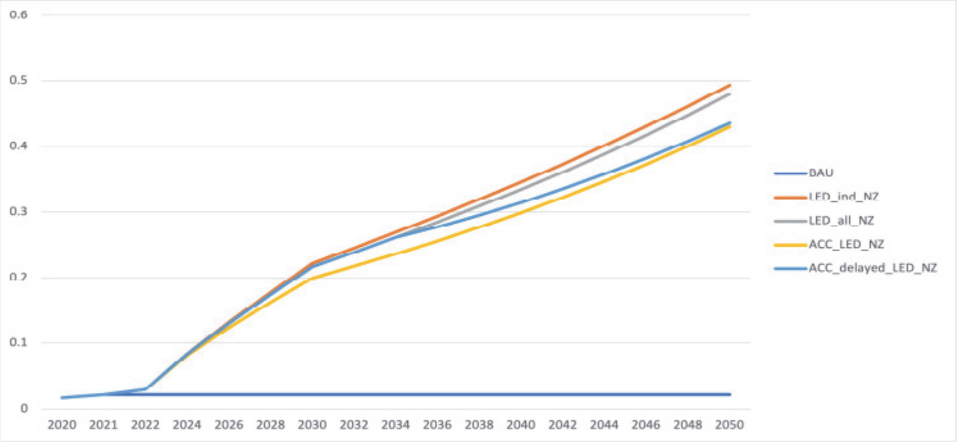
(Unit: %)



Source: The authors.

Figure 54. Korea's carbon price comparison (Net Zero with/without Accelerated Actions)

(Unit: USD 1,000)

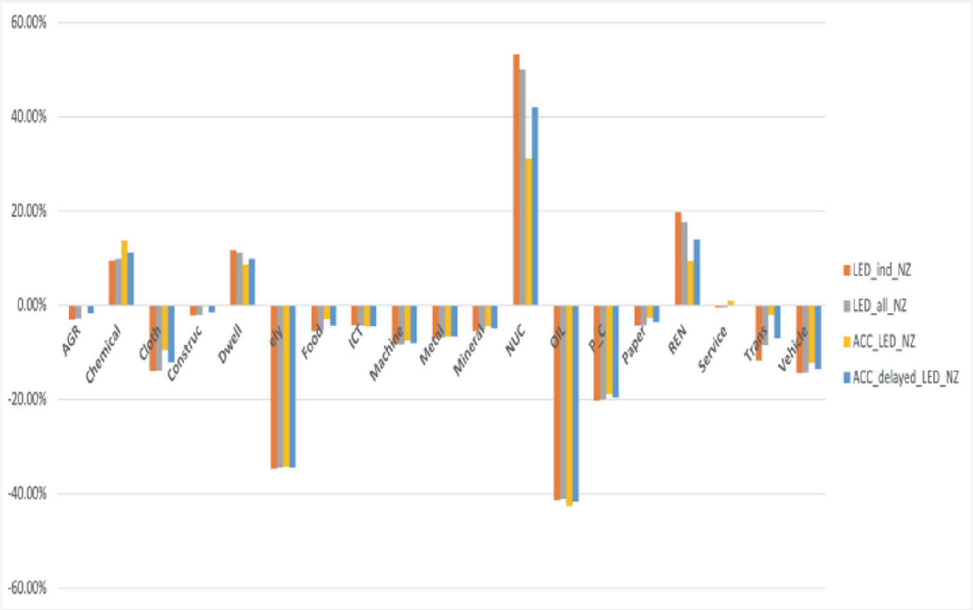


Source: The authors.

Accelerated actions have a more positive impact on production and investment in Korea compared to the net-zero scenario with low energy demand measures. At the sectoral level, accelerated actions lead to slight production gains in many non-energy sectors, including agriculture, chemistry, and transport.

Figure 55. Changes in Korea's production by sector (2021-2050) (accelerated) (relative to BAU)

(Unit: %)



Source: The authors.

5.3 Policy Implications

The results indicated that climate change would lead to an increase in energy consumption and GHG emissions globally. However, the results also indicate that the impact differs significantly by region. Also, if GHG emissions continue to rise, the global temperature rise is projected to exceed 2℃ in the mid-2040s and continue to rise, and it can be expected that the higher the global warming, the higher the resulting cooling and heating energy demands, which could become a vicious circle. The current global CGE model does not reflect new technologies, such as CCS, DAC, and hydrogen, that could be utilized by 2050, which limits the level of GHG emissions that can be reduced in the model. Even under this limitation, the model shows that reducing GHG emissions with net-zero carbon pricing could limit the temperature rise to less than 2℃ by 2050. This implies that the global coordinated efforts of reducing GHG emissions, including the introduction of meaningful carbon prices, are necessary to respond to climate change.

Energy efficiency improvement, which is an important component of low energy demand measures, could lead to rebound effects, indicating an increase in GHG emissions or energy demand. This result is similar to the outcomes of other CGE models suggested in the literature. This suggests that without carbon prices, energy efficiency improvement, which is a typical energy demand intervention in the industry, may not be very effective in reducing energy demand or GHG emissions. However, with a sufficient carbon price, synergistic effects can occur, resulting in a significant alleviation of the economic burden of GHG emission reductions while achieving the same level of GHG emission reductions. Net-zero carbon pricing can lead to negative economic impacts; however, combining net-zero carbon pricing and efforts with energy demand reduction can enhance policy effectiveness and reduce economic damage.

These results show that low energy demand measures alone have limited effectiveness in achieving GHG reduction targets and reducing energy demand. However, it emphasizes the importance of promoting both policies together, as they can generate positive synergies if a sufficient carbon price is applied.

A similar result was observed in Korea as a global case study. It needs to be noted that low energy demand measures can reduce the economic losses caused by carbon prices significantly. Additionally, measures for reducing energy consumption and carbon prices are required to maintain the same level of emission reduction. Improving household energy efficiency and changing consumption structures could be economically beneficial and support GHG emission reduction, but the transition of industrial sectors with high energy use and GHG emissions is key to low-energy demand and a net-zero transition. In the case of Korea, the model shows a significant increase in nuclear power production compared to renewables. Although the model does not take into account technical, social, and political constraints, it can be said that nuclear power has a relatively high potential in achieving carbon neutrality in Korea.

The results indicated that accelerated actions to reduce energy consumption and improve energy efficiency resulted in improved economic outcomes. The national energy policy should not only emphasize energy efficiency improvement but also facilitate innovative technologies and a circular economy for industry sectors. Moreover, raising awareness and incentivizing people to change their behavior towards a low-energy-consuming lifestyle, such as using public transport, walking, or biking, turning down or off cooling and heating devices, and reducing waste, could support the achievement of emission reductions and alleviate the economic burden of the net-zero transition.

Another possible co-benefit is that reducing energy expenditure through mitigation actions or low-energy-demand measures can have a positive impact on well-being. The results of this study show that a global temperature rise is likely to increase cooling and heating energy consumption. The increase in cooling and heating energy consumption implies that rising temperatures cause households to spend more energy and reduce other consumption. This is also associated with negative impacts on the elderly and vulnerable, adverse effects on well-being, and reduced labor productivity due to climate impacts, such as heat waves, which have recently been a focus of widespread discussion. Low energy demand measures and mitigation efforts can be expected to indirectly alleviate these negative impacts, which can also be seen as a positive co-benefit of low demand measures for well-being.

The current CGE model does not consider options other than energy efficiency to reduce energy consumption in industrial sectors, such as shifts in design, circular economy, dematerialization, technological advancements, the introduction of innovative technologies, and resource recycling. Encouraging low energy demand in the industrial sector can reduce the economic burden of GHG emission mitigation. Therefore, besides conventional energy efficiency improvements, the implementation of other measures could result in more significant benefits, and the structural and technological transition of industrial sectors towards low energy use could further enhance the outcomes. It should also be considered that stimulating new industries through this transition could also have positive economic effects.

A transition towards a low-energy-demand world can be beneficial in terms of a just transition. Reducing energy consumption and adopting a low-demand lifestyle could alleviate the economic burden on households by reducing expenditure on energy commodities. Additionally, reduced economic losses could alleviate the economic burden on society, and the utilization of carbon revenues to support low-income or vulnerable groups could support a net-zero transition. Thus, policymakers must design policies and explore strategies for utilizing revenues from carbon pricing to alleviate social costs in transition pathways. Major damages in fossil fuel-related sectors are expected; therefore, the social safety net and policies for supporting those sectors, including the labor force working in those sectors, should be considered. Re-education and job training in the fossil fuel sector could be an option.

5.4 Plan for Model Development

Low demand scenarios can be broadly categorized by a decline resulting from enhanced energy efficiency and behavioral changes. This study assumed the energy efficiency improvement rate exogenously considering previous research results to incorporate the enhancement in energy efficiency into the model. However, this approach has a limitation as it did not account for costs, including investments in new technologies for improving energy efficiency. In particular, the accelerated actions to achieve higher energy efficiency improvements may also increase the associated investments and costs. However, the study did not take into account the investment and costs of energy efficiency improvements, so this part remained as a limitation. Nevertheless, the study validated the rebound effect linked to enhanced energy efficiency and noted that the negative impact of imposing a carbon price was mitigated. Building on this, it might be worthwhile to additionally consider redirecting carbon tax revenues towards technology development and investments for enhancing energy efficiency.

While current CGE models only account for changes in cooling and heating energy demand due to temperature increases, energy demand is affected by a variety of factors, including changes in people's behavior and changing demand patterns due to aging and urbanization. The modules or functions that can reflect changes in energy demand patterns due to aging and urbanization, changes in people's behavior, digitalization, and so on, can be further developed and applied for a more comprehensive analysis of energy demand changes not only due to climate change but also the changes in socio-economic drivers.

In the context of behavioral change, this study assumed a reduction in household energy consumption as an exogenous constraint. However, changes in energy consumption patterns can manifest in various forms, such as the preference for low-carbon or highly energy-efficient products. Nevertheless, due to the aggregated characteristics of sectors in the CGE model, implementing this in a stand-alone CGE model proves challenging. Furthermore, as indicated in several works in the extant literature, many bottom-up models are utilized in energy demand analysis, considering detailed policies, lifestyle changes, and behavioral shifts. The aggregated CGE model has limitations in reflecting these intricacies. Therefore, a more detailed low-demand analysis becomes feasible when incorporating bottom-up models in power, transportation, and industry that allow for individual technology choices. For instance, in the industrial sector, the high capital costs of new facilities can be considered to increase energy efficiency. In transportation, enhanced fuel efficiency of vehicles and reduced demand due to decreased mileage can be realized. Additionally, cooling/heating efficiency improvements through building insulation can be depicted.

The CGE model has limitations in terms of incorporating behavioral changes and reflecting technologies and policies in detail. Therefore, an integrated approach with a more detailed bottom-up model is necessary to assess the potential of low energy demand scenarios. Moreover, innovative technologies such as hydrogen, DAC, and CCS should be included in the model to properly assess net-zero targets. The economic impact of regional carbon prices is significant, and the impact could differ if new low-carbon industries are considered in the future.

Moreover, recent low-demand analyses have emphasized resource efficiency and the circular economy. Further consideration of the circular economy is necessary. Dematerialization or a circular economy could reduce the demand for resources and have other co-benefits, such as energy and resource security, human health, biodiversity, and less environmental pollution. Additionally, they have the potential to reduce GHG emissions because of the reduced use of resources, including fossil fuels, for production.

Additionally, the current model indicates that the prices of renewable energy will become low enough that the final energy demand will increase slightly in the 2040s with a high use of renewable electricity. To address these limitations, it is necessary to incorporate other low-demand measures into the model, such as dematerialization, a circular economy, and design shifts, to reduce energy consumption, including electricity.

Including NGFS scenario analysis, there are increasing efforts to assess the economy-wide or sectoral potential of low demand with IAMs or individual economic or sectoral models. Participating in model comparison projects or sharing knowledge with international research institutes can serve as a starting point for research cooperation.

Additionally, as shown in several previous studies, bottom-up models that can consider more detailed interventions, policies, lifestyles, and behavioral changes are used in energy demand analyses, and aggregated CGE models alone cannot reflect them in detail. Therefore, a more concrete low-demand analysis is possible when sectoral models in power, transportation, industry, and so on, which allow for individual technology choices, are integrated into or linked to the global CGE model. Additionally, it is difficult to reflect behavioral changes in the current model structure, which relies on exogenous assumptions. In this regard, it is necessary to integrate the top-down and bottom-up models for a more concrete analysis.

5.4.1 Top-down/Bottom-up Integration

Many integrated assessment models, such as REMIND-MAgPIE, MESSAGEix, and GCAM, are already used in energy demand studies, as in the NGFS scenario analysis. Current CGE models aggregate regions and sectors, and it is difficult to reflect individual technology choices and behavioral changes, such as in a sectoral bottom-up model. However, integrated models, such as the IIASA's MESSAGE model, with a more detailed representation of technologies and behaviors, are relatively free from these limitations and can reflect technology choice and behavioral change simultaneously. Additionally, the global CGE model used in this study is less detailed than the single-country model and requires considerable data, which poses practical difficulties. Additionally, in future studies, the exogenous assumptions are expected to be better reflected than in this study through the integration of the global CGE model with bottom-up models, such as energy models. Therefore, in future research, it is necessary to integrate more detailed bottom-up models, such as the power and transport sectors, with global CGE models to apply low-demand measures in more detail in these sectors and analyze their economic impacts.

5.4.2 Database

International research institutes use various databases and models, disclose them transparently, and manage their data within a standardized framework. These databases could be used in future studies. Additionally, it is necessary to build a standardized database to facilitate the diffusion of research outcomes. In particular, when building an integrated assessment model, it is necessary to integrate or link models with different characteristics, and it is likely that various databases will be utilized during the model development process. A standardized form of the database can be very useful in such a process. Additionally, because the type and structure of the data utilized by each model are different, it is important to manage them in an organized form. As shown in [Appendix II], the IIASA managed and published 45 datasets, 37 models, and 33 tools in various forms, including databases and scenario explorers (as of January 27, 2024).[51]

Moreover, information on people's behavior regarding energy use, including surveys and real-time data, is likely to become increasingly important when developing low energy demand scenarios and conducting scenario analyses.

5.5 Further Research

The topic of demand is considered an important chapter in Working Group III of the IPCC's 6th Assessment Report and is expected to become increasingly important. In line with this trend, it is necessary to maintain focus on this issue, as it is likely to be a major topic in the IPCC's 7th Assessment Report. In particular, compared to the supply side, which includes technologies such as renewable energy and CCS, the demand side, which also considers social aspects such as behavioral changes, lacks available information and data and has different characteristics by region and country. Hence, an interdisciplinary and comprehensive approach involving collaboration among researchers with various levels of expertise is important for demand-driven research. Particularly, collaboration with international research institutes is important. It is a relatively new topic that is being discussed, and researchers are in the process of setting the direction of research; therefore, it is necessary to examine the types of research being conducted and what is

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[51] IIASA (December 31, 2023), "Models, Tools, and Data", accessed on January 27, 2024.

considered important. Identifying research topics that experts from international research institutions are interested in and learning about various qualitative and quantitative research in the field of climate change and energy, as well as modeling, can be the first step. Establishing a network of young researchers for long-term research cooperation is an important foundation for the development and advancement of new research ideas.

Additionally, it is important to analyze the potential of demand-side actions to achieve mitigation targets and their social, technological, and economic impacts in the Republic of Korea. Historically, energy demand policies focused heavily on energy conservation to maintain a stable energy supply after the oil shock. However, approaches to low energy demand are being increasingly considered to compensate for the limited potential of renewable energy and innovative low-carbon technologies in Korea and to lower social costs in the process of transitioning towards carbon neutrality.

This study provides preliminary results on the economic impact of low energy demand scenarios in Korea. Further studies with scenarios that reflect important measures, such as a circular economy and advanced model settings, could provide better policy implications. Furthermore, it is worth exploring the implications of such changes in energy demand on achieving NDCs and net-zero targets, as well as on responding to international policy changes, such as CBAMs, which were not considered in this study. It is necessary to determine the extent to which shifting to low energy demand and accelerating transitions, such as electrification, are effective in responding to the introduction of foreign carbon trade barriers.

5.6 Topics for Future Research Collaboration with International Research Institutions

To facilitate research cooperation with international research institutions and conduct global-level model development and scenario analysis, it is necessary to understand what research projects are topics of interest at international research organizations. Possible topics for collaboration were selected through meetings and discussions with IIASA experts. Based on the opinions of IIASA experts, this study proposes a selection of research topics worthy of collaborative investigation.

5.6.1 The Circular Economy, Material Cycles, and Their Impact on Energy Demand

The transition to a circular economy is emerging as a global core agenda for improving sustainability, including the implementation of carbon neutrality. However, in Korea, it is difficult to analyze the effects of the circular economy due to inadequate data on waste and circular resource material flows, and the absence of an established classification system. Therefore, it can be helpful when developing a domestic circular economy model by referring to global studies on circular economy modeling, including MESSAGEix-Materials.

Recent developments in the MESSAGEix-Materials model endogenously integrate key material cycles in the MESSAGEix-GLOBIOM framework and link industrial energy and material demand and production. The model represents core production processes along the life cycle (minus extraction), separating primary and secondary production. With the growing importance of the circular economy in future demand transformation (Cantzler et al., 2020), building IAM scenarios utilizing a tighter linkages with circular economy measures could yield deeper insights into the synergistic relationship. The CGE model could also be further developed to consider detailed material-related variables from MESSAGEix, in addition to the energy variables, to investigate the role of circular economy measures at general equilibrium.

5.6.2 Linking Existing Demand Narratives

For the NAVIGATE project (part of the EU's Horizon 2020 initiative), several modeling teams produced scenarios of demand changes following the ASI framework. MESSAGEix also includes an initial set of scenarios based on more detailed demand (BMT) modules. They differ from the more prescriptive LED narratives; however, given the bottom-up nature of the scenarios, they could provide richer insights into the kinds of sectoral transformations necessary under different mitigation targets.

5.6.3 Mitigation Scenarios, a Just Transition, and the Impact on Employment and Other Well-being Indicators

Another important line of inquiry in climate research is exploring how mitigation scenarios can be linked to human well-being. When looking at the limited aspects of the transition, it can be naively expected that demand-focused transformation can have a greater impact on people's quality of life through reduced consumption levels and larger changes in behavior. However, given the multidimensionality of well-being issues, a recent study showed that a demand-focused transition can be more beneficial to human well-being when carefully implemented (Creutzig et al., 2022a). CGE-based models can provide further insights into the economy-wide effects of scenarios that process-based IAMs cannot cover. Employment is one such example, which is directly related to the well-being of people in sectors affected by transitions along mitigation pathways. A recent project by the IIASA (A Just Transition for All) develops additional indicators for well-being assessment in mitigation scenarios. Besides employment, these indicators can be considered for a comprehensive assessment of well-being and a comparison between demand-focused scenarios and more conventional supply-oriented scenarios.

5.6.4 Project-based Research Collaboration

The IIASA primarily operates on a project basis; therefore, research collaboration is possible through participation in individual research projects. For instance, the EU CircEUlar project[52] is a research initiative designed to improve and develop methodologies for circular economy analysis, dealing with the circular economy and resource efficiency, including dematerialization, resource life extension, and waste management. The IIASA is the coordinator of this EU-wide research project, which involves 11 institutions in seven countries. As the circular economy becomes more mainstream in Korea, it may be possible to participate in such projects or conduct related collaborative research to develop and compare models to analyze the potential of the circular economy.

Another example is the SPARCCLE.[53] The SPARCCLE comprises a methodological framework for coupling mitigation and adaptation. It integrates a bottom-up analysis of the multiple dimensions of climate vulnerability, risk, damage, and

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[52] CircEUlar Project (December 13, 2023), "Developing Circular Pathways for an EU Low-carbon Transition", accessed on December 16, 2023.

[53] IIASA (February 22, 2024), "Socioeconomic Pathways, Adaptation, and Resilience to a Changing Climate in Europe (SPARCCLE)", accessed on February 29, 2024.

adaptation with macroeconomic models and top-down integrated assessment studies. This approach is significant because it analyzes climate change mitigation and adaptation from an integrated perspective. If more diverse damage functions and costs can be reflected in the global CGE model, it could be possible to develop an integrated assessment model that can analyze the entire mitigation and adaptation process, which is in line with projects such as the SPARCCLE.

6 Conclusion

Recently, there has been a growing interest in demand-side approaches to energy in both academic and policy areas. The objective of this study is to understand the trends in low energy demand scenario discussions and model developments. This study improves a global CGE model to analyze not only the impacts of global warming on energy demand but also the economic impacts of low energy demand scenarios. Beyond energy efficiency or simple energy saving, policies are being set to encourage the development of advanced technologies while shifting the drivers of energy demand towards lower demand, such as changing people's behavior. In Korea, policies and programs to change the behavior of people and the practices of industries (e.g., energy cashbacks, voluntary agreements, and raising awareness) continue to expand while strengthening existing energy efficiency improvements. While much of the literature has analyzed the impact of activity levels or interventions, there has been little analysis of the aggregate economic impacts of low energy demand scenarios. In particular, no studies have examined the potential of low energy demand measures for GHG emission reduction in Korea. The impacts of temperature increase on energy demand and GHG emissions as well as the economic impacts of low energy demand scenarios analyzed in the study can offer academic and policy contributions. Particularly, the results are expected to serve as a foundation for establishing and expanding the domestic energy demand policies, such as demand efficiency and nationwide awareness on energy demand reductions. Moreover, the study can also contribute to examining the economic effects of energy demand measures under GHG reduction efforts in Korea as well as globally.

To conduct such an analysis, the changes in cooling and heating energy demands due to global warming were analyzed. The impact of COVID-19 was indirectly considered in the GDP and population projections taken from the updated SSP scenario of the EU NAVIGATE Project, which considers the impact of COVID-19. Next, carbon prices from the NGFS Phase 4 net-zero scenario were applied as a carbon pricing scenario to examine the possible economic and environmental impacts of a net-zero transition. Based on previous studies and the model structure, energy efficiency improvements in industry and households were selected and household energy consumption reduction as representative low energy demand measures, and the economic impacts of implementing these measures were examined.

This study applied the climate module of the FUND model and a damage function to calculate cooling and heating energy demand changes. As a result, a rise in global temperature will lead to increased demand for cooling and heating energy, and the higher the global mean temperature, the more rapidly this demand will grow globally. This indicates that an increase in global and regional temperatures can, in turn, lead to higher GHG emissions, which may further raise temperatures. In doing so, it can hinder the efforts to reduce energy demand.

Overall, the results of this study indicate that the implementation of carbon prices to reduce GHG emissions could have negative economic impacts on GDP, industrial production and investment, and other economic indicators, particularly in fossil-fuel-related sectors. While there are differences by region, the trends are broadly similar, and similar results are also found for the Republic of Korea. There is a significant transition occurring among industries, highlighting the need for policies that facilitate such transition. There will be an increased focus on Just Transition, as well as the development of technologies and policies to accelerate the transition. If production and investment in existing fossil-fuel-based or energy-intensive industries decline, job losses and stranded assets will increase. While the model suggests a transition to other sectors, in practice, this will require significant policy responses, such as retraining programs, policies to reduce stranded assets, and support for local economies around fossil fuel and energy- and emission-intensive industries.

The low energy demand measures examined in this study, such as improving energy efficiency in industry and households and reducing household energy consumption, would reduce the economic burden of transition. In addition to lowering the carbon prices required to achieve the same emission reductions, it was found that those measures also increase the real GDP relative to the NZ scenario, and have positive impacts on production and investment in non-energy sectors in general. These results emphasize the need for energy demand policies, including energy demand efficiency and the promotion of low-carbon and low-energy lifestyle, which have recently been considered as Net Zero policies. In particular, the large impact of energy efficiency improvements in industry highlight the need for continuous efforts and the need to go beyond traditional energy efficiency improvements to include efforts such as energy management systems and process optimizations. It is worth considering the introduction or design of a principle similar to the EU's Energy Efficiency First Principle, which explicitly reflects efforts and measures towards increasing energy efficiency in policy and investment decisions for sectors that can impact energy demand or energy systems. Additionally, it is crucial to support the adoption of innovative technologies. Other policies to consider include providing incentives for behavioral changes and designing urban development plans that decrease energy consumption from the outset. These efforts could not only reduce the socio-economic impacts of the transition towards carbon neutrality, but also contribute to reducing the burden on the supply side.

However, the structural limitation of the model and a limited range of low energy demand measures considered in this study should be addressed in further research. The model's structure can suggest a limited ability to analyze carbon neutrality due to its lack of consideration for innovative technologies such as CCS and hydrogen. In addition, low demand measures are typically detailed interventions, but the sectors in the CGE model are quite aggregated. Hence, it is necessary to utilize an integrated model linked to sectoral models to reflect those individual or a set of measures. Furthermore, research should be conducted to incorporate reductions in energy and material demand in industry, such as circular economy and dematerialization, which have recently gained importance, in order to provide a more comprehensive analysis of low energy demand scenarios.

Cooperating with international research institutes, renowned for their expertise in modeling and scenario analysis, is necessary to facilitate low energy demand analysis and advance the model in an efficient and effective manner.

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Appendix

A. The MESSAGEix Model in Detail[54]

IIASA has led the research and development of an integrated assessment model (IAM) and energy-related research globally. The organization's in-depth understanding of the model reflects its deep well of modeling analysis know-how and makes it a valuable partner in collaborative research efforts.

The MESSAGEix-GLOBIOM model is an IAM developed by the International Institute for Applied Systems Analysis (IIASA) used to assess the long-term impacts of energy and climate policies by combining energy-environment-economic systems (Huppmann et al., 2019). The MESSAGEix-GLOBIOM model framework comprises five specialized modules, or models: 1) MESSAGE, an energy model (Model of Energy Supply Alternatives and Generic Environmental Impacts), 2) GLOBIOM, a land use model (Global Biosphere Management), 3) GAINS, an Air Pollution and Greenhouse Gas Model (Greenhouse Gas-Air Pollution Interactions and Synergies), 4) MACRO, an aggregated macroeconomic model, and 5) MAGICC, a Simplified Climate Model (Model for Assessing Greenhouse Gas-Induced Climate Change).

MESSAGE and GLOBIOM play central roles in this suite. They are optimization models featuring detailed implementations of energy production technologies, which are optionally coupled with the three other models above to exchange important feedback and additional limitations from outside the energy system. Crucial inputs to the model involve GDP and population projections (primarily based on the SSP framework), energy resource endowments, energy switching rates in the supply chain, the pace of technological change, fixed and variable costs of technologies, macroeconomic variables such as energy demand, policy constraints, and discount rates, and land use and emission factors. Output variables from each scenario include greenhouse gas emissions at the regional and national levels, prices of energy goods, land use, and output (e.g., activity or capacity installation) by technology.

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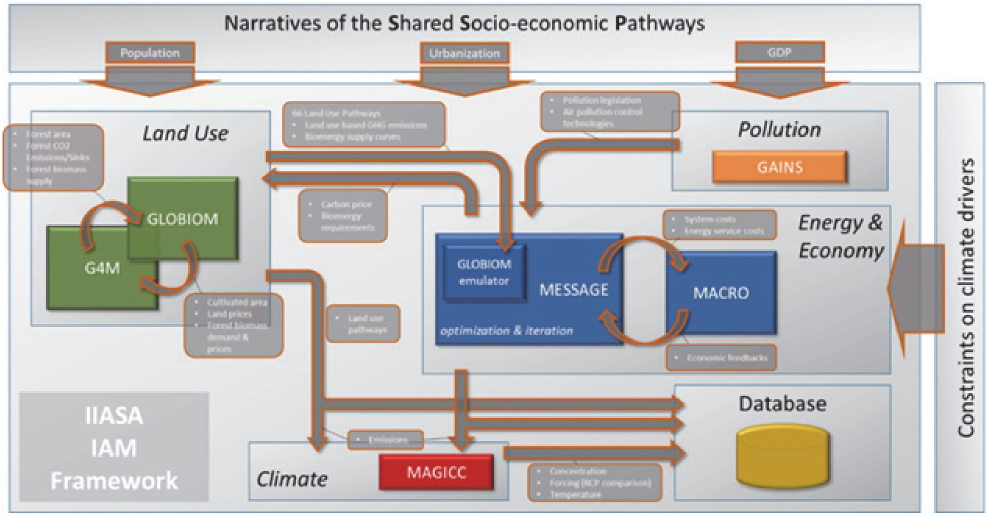
[54] Min (January 15, 2024), internal document.

A.1 Standard MESSAGE Model Structure[55]

The MESSAGE model is a linear programming model used to perform system-wide optimizations that meet a given energy demand at the lowest cost. The optimization process occurs iteratively in conjunction with MACRO, a single sector macro-economic model. MACRO produces estimates of macroeconomic demand given from the energy system and service costs computed by MESSAGEix. In the six commercial end-use demand categories outlined in MESSAGE (see the section on energy demand), MACRO adjusts demand for useful energy based on prices. This adjustment continues until both models achieve equilibrium. This iterative approach captures changes to energy efficiency induced by price changes in the energy system.

Figure A 1. Structure of IIASA IAM (MESSAGEix-GLOBIOM)



Source: Fricko et al. (2017), p.259.

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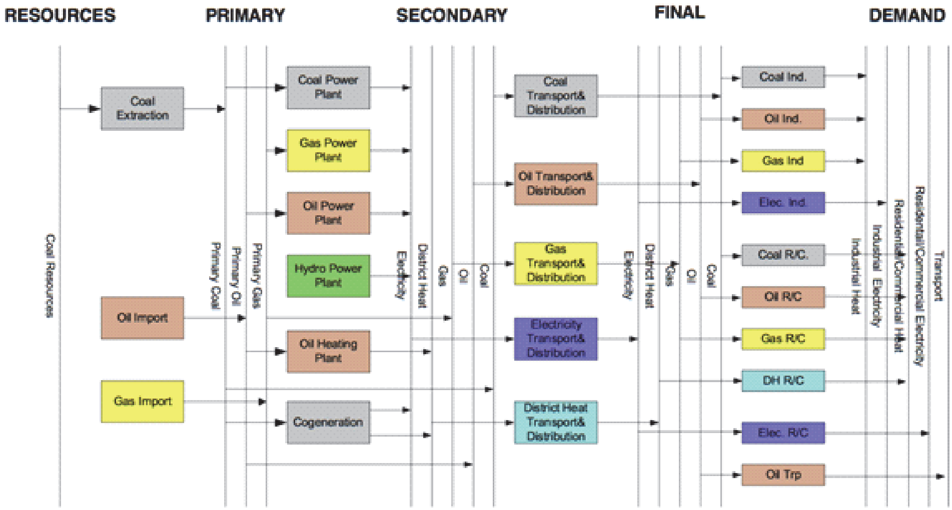
[55] Further technical documentation and data for the model is available at IIASA (May 4, 2022), "MESSAGEix-GLOBIOM Documentation", accessed on October 16, 2023.

A.2 Key Aspects of the Standard Model Framework

Within the MESSAGE model, the energy system is structured into five levels: resources, primary energy, secondary energy, final energy, and demand (useful energy). Figure 2 illustrates a basic, but partial Reference Energy System (RES), forming the foundation for MESSAGE.

The mathematical formulation of MESSAGE is grounded in the technologies represented by the rectangles in Figure A 2. These technologies are responsible for converting, utilizing, and producing energy commodities across different levels. They contribute crucial information to the optimization problem, detailing the conversion of physical quantities of variables such as fossil fuels and renewable resources, emissions, information on associated costs, facility lifetimes, and other relevant parameters.

Figure A 2. Example of a Reference Energy System (RES) in MESSAGE



Source: van Ruijven and Min (2020).

(1) Technology

Technology is a fundamental component within the MESSAGE model, connecting various stages in the supply chain of the baseline energy system. In MESSAGE, energy technologies get a spectrum of inputs, including economic factors such as investment costs and operational expenses, technical parameters such as conversion efficiency, ecological considerations such as emissions, and socio-political characteristics, including policy constraints. The model has the capacity to impose limitations or exclusions on the deployment of specific technologies in different regions or at different points in time. Technical parameters, incorporating capacity limits, operational constraints, and growth rates over time, contribute to representing inertia in the system and engineering constraints on technology diffusion. Detailed vintage structure information for each technology in MESSAGE enables the model to account for temporal variations, such as lower efficiency or higher operating and maintenance costs as facilities age. In addition, the model autonomously determines the optimal time to retire a facility based on fixed costs per unit of capacity and variable/operating costs per unit of operation, allowing for a nuanced differentiation between technical life and economic life contingent on market conditions; that is, when retiring a facility becomes cost-optimal due to expected future revenues falling below fixed and operating costs.

(2) Exhaustible Resources

Exhaustible resources, notably fossil fuels, constitute the initial level in the energy system within MESSAGE. Given their pivotal role in shaping the outlook of the energy system and prospects for carbon reduction, understanding changes in availability and mining costs across SSPs is crucial. MESSAGE bases its assumptions of fossil fuel resources on various sources (Riahi et al., 2012; Rogner, 1997), aligning with the narrative structure of each SSP. Although the physical resource base remains consistent across SSPs, significant differences are assumed in the technical and economic availability of resources, particularly unconventional oil and gas resources. The economic viability of a resource is ultimately determined by the cost of providing energy services, not just extraction costs. Technological change in fossil fuel extraction and conversion technologies varies across SSPs, with SSP3 anticipating rapid change, emphasizing coal technology, and anticipating synthetic fuels from coal liquefaction in the long term. SSP2 continues existing trends, focusing on technological development of unconventional hydrocarbon resources. Uranium resource estimates, vital for advanced nuclear fuel cycles, exhibit a wide range in the literature, impacting scenarios in MESSAGE. The model incorporates advanced nuclear fuel cycles in principle, but their availability depends on scenario specifics. To represent cost characteristics, commodities in MESSAGE are categorized into different resource classes, each with an upper bound on cumulative extraction, allowing for the implementation of resource supply curves where cheaper resources are utilized first.

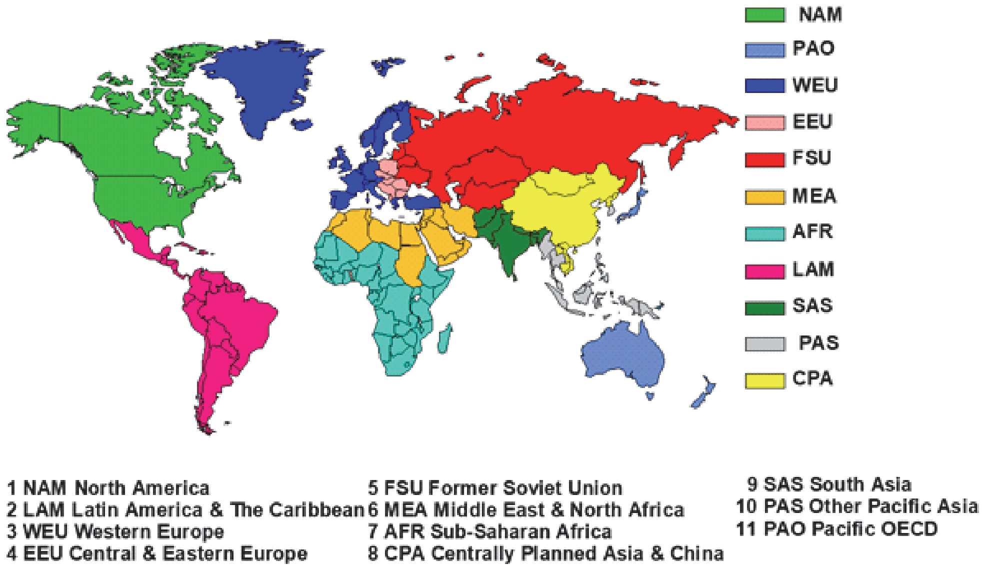
(3) Renewable Resources

The assumption guiding the supply of renewable energy resources follows a tiered structure, drawing from existing IIASA research, wherein sites with higher quality conditions for wind and solar power are prioritized and installed before progressing to sites with lower quality resources (Sullivan et al., 2013). Consequently, with the rapid development of renewable resources, there is an associated increase in the installed capacity needed per unit of energy produced. This sets renewable energy apart from non-depletable resources, where extraction costs typically rise as reserves are developed.

(4) Native Spatial and Temporal Disaggregation

For designing and exploring scenarios to address diverse research requirements, it is crucial to adeptly manage varying levels of spatial and temporal granularity. Consequently, MESSAGE implementations may structure the underlying data to accommodate scenarios where certain technologies or products are assessed at a broader regional or annual average level, while other elements are scrutinized with a finer spatial or temporal resolution. Technologies falling into the former category encompass data over larger geographic or temporal scales (coal mining and similar activities). These technologies are those for which considerations such as seasonal variability and local transportation infrastructure are generally of less significance. Conversely, detailed information is often essential for power generation or river basin water consumption to precisely capture impacts on the biosphere and sectoral interdependencies. This approach streamlines effective scenario development, alleviating the computational burden by modeling only those sectors at the necessary level of detail. The recent standard spatial resolution of the MESSAGE model involves 11 regions globally (or 12 when China is separated from the CPA).

Figure A 3. Spatial organization of the MESSAGE model



Source: MESSAGEix-GLOBIOM (March 18, 2021), “Regions”, accessed on January 12, 2024.

(5) Emission and Pollutants

The MESSAGE model is frequently utilized for comparing and delineating energy supply trajectories within the constraints of greenhouse gas emissions. As such, the model incorporates formulas designed to impose limits on emissions and pollutants. These formulas aggregate emissions, ensuring that a predefined cap for a particular region constrains total emissions from all subregions to the larger region. Additionally, these formulas offer flexibility, allowing configuration to specifically consider emissions from certain types of technologies or land use scenarios, or to restrict (average) emissions over a specified time period.

(6) Land-use Model Emulator

The nexus between the land use and energy sectors constitutes a pivotal aspect of IAM, given that land use plays a dual role in supplying bioenergy and food for human societies while simultaneously serving as a source and sink of carbon dioxide. However, integrating agriculture and forestry seamlessly into a technology-based energy system models poses challenges. Consequently, the MESSAGE implementation incorporates a versatile land use model emulator, as opposed to an independent model itself. This emulator can determine linear combinations of land use scenarios, taking into account cost characteristics, emission factors, commodity outputs (such as crops and bioenergy), and input factors such as fertilizers. The current parameterization of land use scenarios is derived from the GLOBIOM model, developed and maintained by IIASA.

The land-use emulator incorporates a set of land-use scenarios into the MESSAGEix energy system model. Represented in a two-dimensional scenario matrix, these land-use scenarios combine diverse carbon and biomass price trajectories. This matrix enables the depiction of biomass supply curves contingent on various carbon prices and marginal abatement cost curves dependent on different biomass prices for the land-use sector within MESSAGEix.

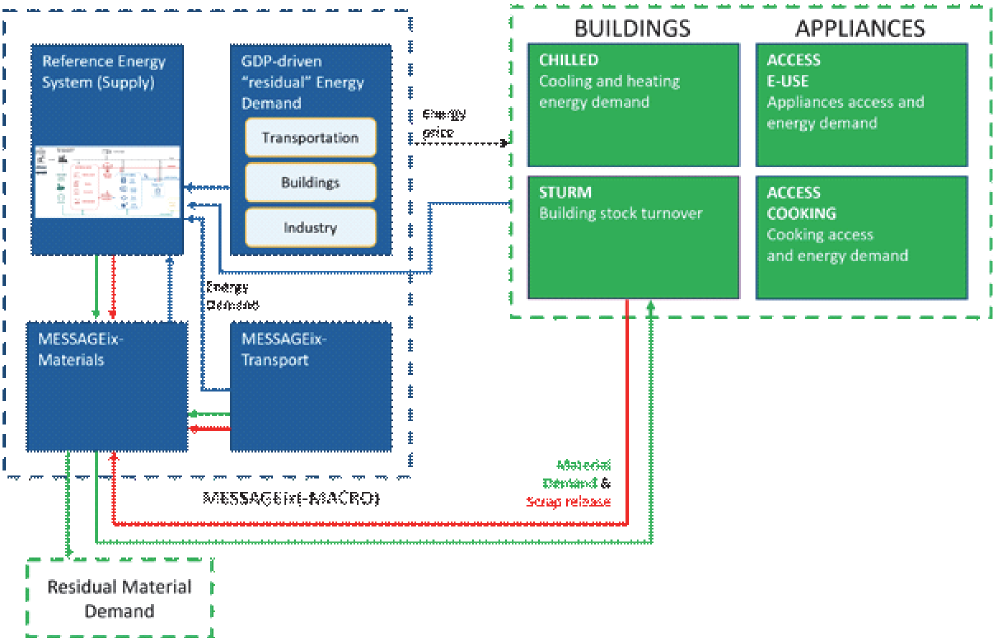
(7) Energy Demand

When linked with MACRO, the demand for energy services is responsive to shifts in energy prices, but without the link, it is considered exogenous to the MESSAGE model. The iterative solution of linear MESSAGE equations and nonlinear MACRO models can pose numerical challenges, necessitating checks for oscillations in the solution during the iterative process. The standard MESSAGE model categorizes demand into three economic sectors (industry, buildings, and transportation) and includes feedstock and non-commercial biomass demand, resulting in seven distinct types of demand: industrial electricity, industrial heat, industrial feedstock, non-commercial biomass, residential and commercial thermal, residential and commercial specific demand, and transportation. Future demand is projected by overlaying estimates of future GDP and population onto quantile regression results derived from historical country-level data on GDP per capita and final energy use.

(8) End-use Modules

So far, we have described the structure of the standard or core MESSAGEix model, focusing on representing the energy supply. Lately, to address the increasing emphasis on energy demand, ongoing efforts are being directed toward the development of distinct detailed models for industry, buildings, and transportation, expanding upon the core MESSAGE model. These are collectively referred to as the BMT (Buildings, Materials, and Transport) modules of MESSAGEix. These individual models aim to articulate demand in terms of fundamental energy services as much as possible, such as square meters of floor space in buildings, rather than relying on exogenous final or useful energy projections for the building sector. A diverse range of demand-side technologies implemented in the BMT modules fulfills service demand, facilitating a more nuanced comprehension of potential technological shifts within these sectors. The flexibility of attaching or detaching each BMT module to the core MESSAGEix model is a key feature, allowing customization based on the specific nature of the problems being addressed. Variants of MESSAGEix-GLOBIOM are named MESSAGEix-GLOBIOM x.x-(BMT)-Rn, where n refers to the number of regions, and x.x is the version number. NGFS scenarios built with MESSAGEix-GLOBIOM 1.1-M-R12, for example, need only contain the identifier for the detailed industry module.

Figure A 4. Overview of the MESSAGEix-Model extended with the BMT modules

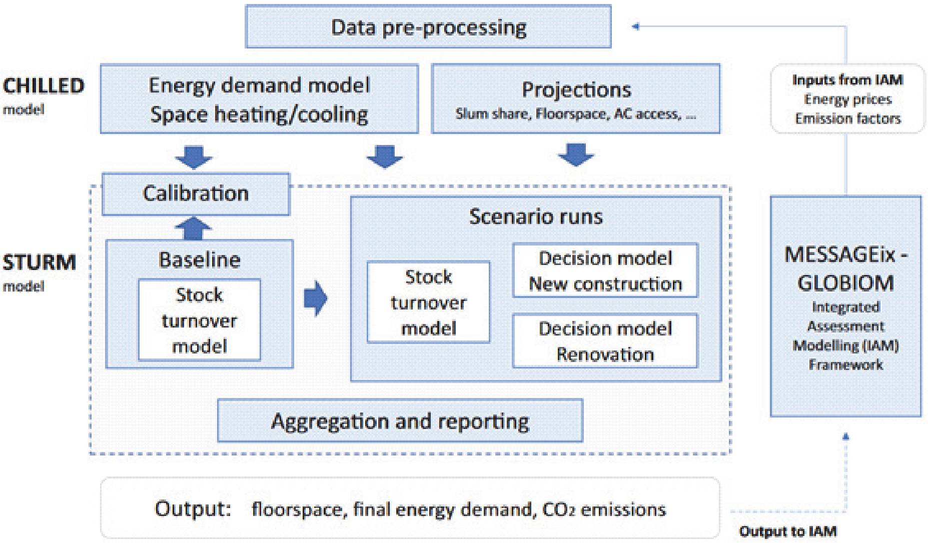


Source: Min (January 15, 2024), internal document.

(9) Buildings (MESSAGEix-Buildings)

MESSAGEix-Buildings functions as a comprehensive framework for modeling energy demand in the building sector across diverse scenarios incorporating socio-economic, technological, climate, and policy considerations (Mastrucci et al., 2021). Comprising two sub-modules, CHILLED and STURM, it employs a bottom-up engineering approach and a stock turnover model, respectively, to estimate space heating and cooling demand and assess various activities, including new construction starts, demolitions, renovations, and energy efficiency decisions. This framework is characterized by flexibility in temporal and spatial resolution, facilitating a highly detailed representation of the residential sector, including critical household dimensions (location, income, and tenure) and building characteristics (housing type, energy efficiency standard, and fuel use). Input data encompass basic demographics, socio-economic projections, and building-related information, with additional projections for intermediate variables such as floorspace, slum population, and access to air-conditioning. CHILLED calculates energy demand intensity for existing and future building cohorts, while STURM reconstructs the building stock configuration for the base year and projects characteristics and energy demand based on inputs from MESSAGEix. The overall structure is shown in Figure A 5.

Figure A 5. MESSAGEix-Buildings framework



Source: Mastrucci et al. (2021).

(10) Industry (MESSAGEix-Materials)

MESSAGEix-Materials serves as an extension module designed to incorporate material flows and life-cycle accounting into MESSAGEix-GLOBIOM framework (Ünlü et al., forthcoming). This module explicitly represents technologies and processes from four key energy- and emissions-intensive material industries: steel, cement, aluminum, and petrochemicals. The life cycle representation adopts a generic structure called the Reference Material System (RMS), analogous to the Reference Energy System (RES) used in energy system modeling. This structure is customized to account for process-specific differences between industries. The life cycle stages modeled include production, Finishing and manufacturing, end of life, and scrap recovery and recycling, allowing for the ongoing development of the module to reflect diverse material efficiency and circular economy strategies. Similar to the representation of energy commodities in MESSAGEix, materials in different life cycle stages are categorized accordingly. However, resource extraction, such as iron ore and bauxite, is not explicitly represented in MESSAGEix-Materials at the current stage. The production phase involves selecting technologies for primary production based on their commercialization and decarbonization potential, while finishing and manufacturing processes result in a generic product. During the manufacturing process, a fixed percentage of new scrap is formed, characterized by higher quality and direct use within the manufacturing process, distinguishing it from old scrap formed at the end of a product's life cycle.

(11) Transport (MESSAGEix-Transport)

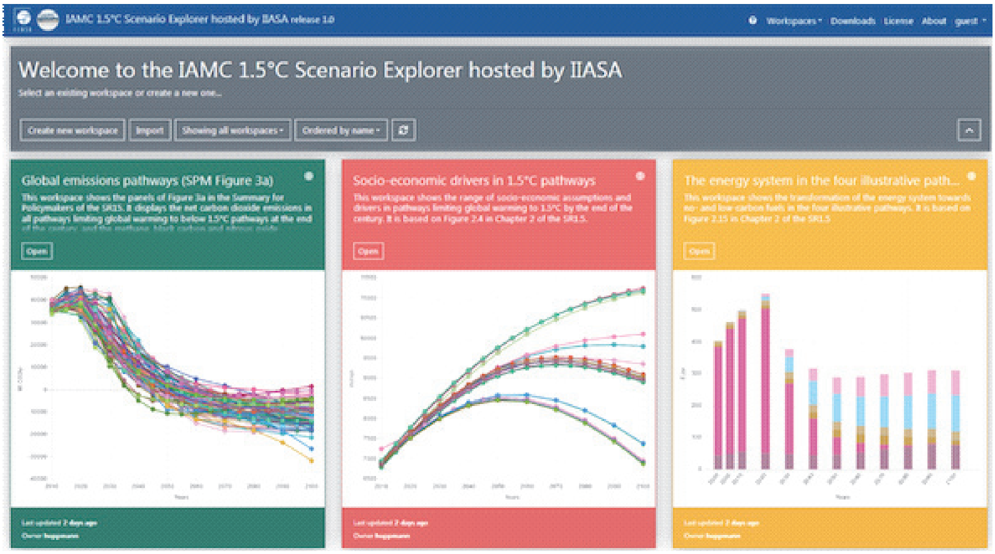
The detailed transport module in MESSAGEix-Transport provides a comprehensive representation of individual transport modes and technologies, incorporating a model of modal shifts that considers relative costs in terms of time and money across different travel modes (McCollum et al., 2017). This detailed approach is crucial for improving the understanding of heterogeneity and behavior within the light-duty vehicle (LDV) sub-sector. LDV drivers in MESSAGEix-Transport are categorized based on settlement patterns, attitudes toward technological adoption, and vehicle usage intensity, resulting in 27 unique consumer groups within each of the R11 model regions. The allocation of current and future vehicle demand is determined by considering base-year transport statistics, population projections, and diffusion theory, utilizing data sources such as the US National Household Travel Survey (NHTS). MESSAGEix-Transport assigns disutility costs to potential vehicle technologies. These costs vary by technology, consumer group, country/region, and over time, are derived using a specialized version of the MA3T vehicle choice model. This employs a Nested Multinomial Logit (NMNL) discrete choice approach and has been developed to study LDV transition in the US up to 2050. This comprehensive transport modeling framework facilitates a nuanced understanding of consumer behavior, technological choices, and their life cycle impact.

B. IIASA Databases and Models

B.1 IIASA Scenario Explorer

The IIASA Scenario Explorer is being increasingly used by the research community in outreach and model comparison projects. For example, there are explorer instances accompanying the IPCC SR1.5 and IPCC Sixth Assessment Report. The IAMC 1.5℃ Scenario Explorer was the first application of the IIASA modeling platform infrastructure. The 2024 update of the Shared Socioeconomic Pathway Scenario Database will be included in the Scenario Explorer.

Figure B 1. The IAMC 1.5℃ Scenario Explorer



Welcome to the IAMC 1.5°C Scenario Explorer hosted by IIASA

Select an existing workspace or create a new one...

Global emissions pathways (SPM Figure 3a)

This workspace shows the panels of Figure 3a in the Summary for Policymakers of the SR15. It displays the net carbon dioxide emissions in all pathways limiting global warming to below 1.5°C pathways at the end

Last updated 2 days ago
Owner huppmann

Socio-economic drivers in 1.5°C pathways

This workspace shows the range of socio-economic assumptions and drivers in pathways limiting global warming to 1.5°C by the end of the century. It is based on Figure 2.4 in Chapter 2 of the SR1.5.

Last updated 2 days ago
Owner huppmann

The energy system in the four illustrative path...

This workspace shows the transformation of the energy system towards no- and low-carbon fuels in the four illustrative pathways. It is based on Figure 2.15 in Chapter 2 of the SR1.5

Last updated 2 days ago
Owner huppmann

Source: IIASA (August 8, 2019), "IAMC 1.5℃ Scenario Explorer Hosted by IIASA, Release 2.0", accessed on January 27, 2024.

The Scenario Explorer is built around the concept of workspaces, which can be developed, saved, and shared between users. Workspaces are interactive, user-customizable environments that can contain charts, data-tables and text descriptions. Any registered user of the Scenario Explorer can create, save and share workspaces. Workspaces can be generated to be public such that every user sees them when accessing the Scenario Explorer instance or they can be shared bilaterally with colleagues or on social-media. Charts, data tables, and text descriptions within a workspace are called panels. New panels can be created in the same scenario across multiple panels for easy comparisons.

Documentation is provided at the level of individual panels (using the document icon) or for the full database in the documentation menu at the top of the Scenario Explorer. Definitions and links to more detailed documentation and references are provided for all models, scenarios, variables, regions, and metadata categories that are used for scenario categorization.

The data of an individual panel can be downloaded in several different formats (including Microsoft Excel and csv) or the figure itself can be downloaded as a PDF file or in another image format. The data contained in the full database can be downloaded through the download menu at the top of the Scenario Explorer. This menu contains snapshots in csv format for all scenarios and variables in the database, as well as the reference data and citation options for the data in different formats.

B.2 IIASA Models and Database

The IIASA has collaborated with several international and national research institutes, universities, and organizations. To facilitate further cooperation and promote research outcomes, the IIASA hosts a web site featuring all scenario explorers, databases, and models that the IIASA owns or participates in. As of January 27th, 2024, the IIASA has published 45 datasets, 37 models, and 33 tools.56)

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56) IIASA (December 31, 2023), “Models, Tools, and Data”, accessed on January 27, 2024.

Table B 1. Examples of IIASA models and databases

Scenario Explorer and Database	
Shared Socioeconomic Pathway Scenario Database (SSP)	Dataset of Shared Socioeconomic Pathways and related Integrated Assessment Scenarios
NGFS-IIASA Scenario Explorer	Updated Climate Scenarios for assessing climate-related risks
AR6 Scenario Explorer and Database	Model-based pathways in IPCC AR6
IAMC 1.5-degree Scenario Explorer	Model-based mitigation pathways in Special Report on Global Warming 1.5-degree
Models	
Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)	Model for assessing emission and pollution reduction strategies
Global Biosphere Management Model (GLOBIOM)	Global model for assessing competition for land use between agriculture, bioenergy, and forestry
Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGEix)	Modeling framework for mid- to long-term energy system planning, energy policy analysis, and scenario development
Global Agro-Ecological Zones (GAEZ)	Tool for detailed assessment of available resources (sustainable production of food)
Community Water Model (CWatM)	Model for assessing the future water demand and availabililty
Global Forest Model (G4M)	Model for assessing forest growth, stock, harvest amount
Database	
Harmonized World Soil Database	Global soil database
Global Forest Database	Global forest map database

Source: IIASA (December 31, 2023), "Models, Tools, and Data", accessed on January 27, 2024.

Executive Summary in Korean

글로벌 CGE 모형을 활용한 저에너지 수요 시나리오 연구

1. 연구의 배경 및 목적

❑ 에너지 수요에 대한 전세계적인 관심이 높아지고 있음

- ㅇ IPCC 6차 평가보고서, NGFS Phase 4 등 글로벌 연구에서 수요 측면의 대응을 강조하고 있음
  - IPCC 6차 평가보고서에서는 ‘수요’ 챕터를 별도로 구성하여, 수요 측면 대응의 중요성과 온실가스 감축 잠재력에 대해 강조하였음
  - 예시적 완화경로(IMPs)의 하나로 자원의 효율적 사용 등 수요 측면의 수단을 고려한 IMP-LD 경로가 제시되었음
- ㅇ 에너지 효율 향상, 행태 변화와 같은 수요 측면의 대응은 비용 효율적이며 효과적인 온실가스 감축 수단이며, CCS와 같은 공급 측면의 부담도 줄일 수 있을 것으로 기대됨
- ㅇ 다음 IPCC 7차 평가보고서에서 에너지 수요 이슈가 보다 강조될 수 있으며, 수요 측면의 대응이 가져오는 경제적, 환경적 편익에 대한 국가 정책의 관심이 높아지는 만큼, 저에너지 수요 시나리오에 대한 정량적인 분석이 필요함

❑ 저에너지 수요를 구성하고, 글로벌 CGE 모형을 활용하여 저에너지 수요 수단들이 국내 및 글로벌 온실가스 감축에 기여할 수 있는 잠재력을 정량적으로 분석함

- ㅇ 본 연구는 선행연구 및 정책에서 고려되는 산업 및 가계의 저에너지 수요 수단들을 찾고, 이를 글로벌 CGE 모형에 적용함으로써 저에너지 수요 시나리오의 국내 및 글로벌 영향을 종합적으로 살펴볼 수 있음
- ㅇ 전세계 온실가스 배출에 따른 기온 상승과 이에 따른 에너지 수요 변화를 분석할 수 있는 글로벌 CGE 모형을 구축함으로써, 다양한 국내 및 글로벌 온실가스 감축 정책 및 시나리오 분석에 활용될 수 있을 것으로 기대됨

- 해외 연구기관인 IIASA 연구진과의 연구 협력을 통하여 네트워크를 구축하며, 향후 지속적인 연구 협력을 위한 연구 주제를 발굴하여 구체적인 연구 협력을 위한 기반을 구축할 수 있을 것으로 기대됨

2. 에너지 수요 및 모델링 분석 연구 동향

❑ 저수요 시나리오 개발 연구 동향

- Grubler et al. (2018)은 저에너지 수요 시나리오에 대한 내러티브를 제시하였으며, 이를 기반으로 다수의 저수요 시나리오가 구축되었음
- IPCC 6차 평가보고서에서는 IMP-LD 시나리오를 예시적 완화경로의 하나로 제시하였으며, NGFS Phase 4에서도 저수요 시나리오가 포함되었음. 이는 전 세계적으로 저수요에 대한 관심이 높아지고 있음을 나타냄
  - IPCC 6차 평가보고서의 IMP-LD는 에너지를 포함한 자원의 효율적 사용과 소비 행태의 전환을 강조하였으며, 다른 예시적 완호경로에 비해 바이오에너지-탄소 포집 및 저장(BECCS)의 사용이 적은 것이 특징임
  - NGFS Phase 4의 저수요 시나리오는 전체 7개 시나리오 중 낮은 수준의 물리 및 이행 리스크 수준을 나타냄

❑ 저수요의 잠재력에 대한 연구도 다수 진행 중임

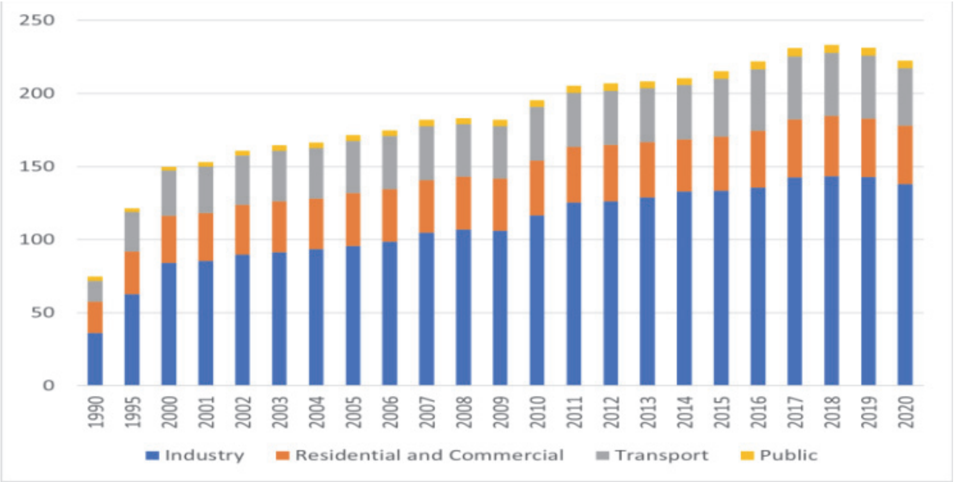
- IPCC 6차 평가보고서에서는 수요를 별도의 챕터를 구성하여 강조하고 있으며, 최종에너지 수요의 회피(Avoid), 전환(Shift), 개선(Improve)에 대한 검토 및 분석을 수행함
  - 수요 측면 접근법은 2050년까지 건물, 육상 운송, 식량 부문의 온실가스 배출량을 40-70% 감축할 수 있는 잠재력이 있을 것으로 강조되고 있음
- World Economic Forum(2024)에서도 에너지 수요 전환의 중요성에 대해 강조하며, 에너지 수요를 줄이기 위한 노력을 통해 2030년까지 에너지 소비를 30% 줄일 수 있을 것으로 전망하며, 연간 2조 달러의 영향을 미칠 수 있음을 강조하였음
  - 낮은 인식, 수요를 줄이기 위한 수단 및 조치의 충분하지 못한 수익률, 정책 지원 부족 등이 에너지 수요 감축을 활성화하는데 방해하고 있음
- 이 외에도 에너지, 수송, 건물 등 개별 부문에 대한 수요 정책 및 수단에 대한 연구들과 함께 에너지 효율 향상, 에너지 소비 행태 변화 등에 대한 연구가 이뤄지고 있음. 이러한 연구에는 부문 별 모형, 계량경제학 모형, 통계적 방법론 등이 다양하게 활용되고 있음

❑ 수요 측면의 정책에 대한 관심도 높아지고 있음

- o 한국은 2022년 에너지 수입의존도가 94%에 달하는 에너지 수입국으로, 에너지 수급 균형 및 에너지 안보 측면에서 에너지 수요 관리에 대한 관심이 많았음
  - 2021년 최종에너지 소비량은 181.7백만 TOE로 세계 10위 수준이며, 석유와 천연가스 수입은 OECD에서 각각 5위와 6위 수준임
  - 2021년 최종에너지 소비의 약 63.3%가 산업 부문에서 이뤄지고 있으며, 수송 부문과 가정 및 상업 부문이 각각 16.9%와 17.4%임 (KEEI, 2022, pp.280-285)

〈그림 1〉 부문별 최종에너지 소비

단위: MTOE



자료: KESIS(2022.11.15), “최종에너지 소비 (연간; 열량)”, 검색일: 2024.1.2.

- o 국내 최종에너지 소비는 2022년부터 2027년까지 연평균 0.8%씩 증가할 것으로 전망되고 있음
  - AI, ICT 도입, 전기차 확대 등 경제 및 기술적 변화와 함께 저출산, 고령화 등 인구구조의 변화는 미래 에너지 소비 구성 및 전망에 영향을 미칠 것으로 전망되고 있음

❑ 한국의 에너지 수요 정책

- o ‘시장원리 기반 에너지 수요효율화 종합대책’은 산업, 가정 및 상업용 건물, 수송 부문의 에너지 효율 향상을 위한 지속적인 노력을 강조하고 있음

- o 자발적 협약을 비롯하여 에너지 효율 향상에 초점을 맞춘 다양한 정책이 시행 혹은 계획되고 있음
  - 에너지이용합리화법은 1970년대부터 에너지 다소비 부문을 포함하여 산업의 에너지 효율 개선을 주도해 왔음
  - KEEP 30 프로그램은 2023년부터 2027년까지 5년간 연평균 1% 이상의 에너지 효율 개선을 목표로 하며, 정부와의 협약을 통해 30개 에너지 다소비 기업이 에너지 효율 개선을 달성하면 인센티브를 제공함
  - 전기자동차 대상 전비등급제, 중대형 승합 및 화물차 연비제도 도입 등 수송 부문에서도 효율 향상을 위한 노력이 이어지고 있음. 건물 부문에서도 건물 에너지 효율을 향상시키기 위한 정책이 도입되고 있음
- o 에너지 효율 향상 이외에도 교육 기반 구축, 정보 공유, 소통 활성화 등 장기적인 변화를 가져올 수 있는 정책을 비롯하여 사회를 변화시키기 위한 정책들이 도입되고 있음
  - 건물의 냉난방 권장온도, 에너지 절약 캠페인, 탄소중립 실천사례 공유 등 행동을 변화시키기 위한 노력도 이어지고 있음
  - 에너지 캐시백 프로그램은 주택용 전기를 사용하는 고객들이 직전 2개년 동월 평균 대비 3% 이상의 전력 사용량을 줄이게 되면, 인센티브를 제공하여 소비자들의 행동 변화를 유도하고 있음
- o 산업, 건물, 수송 부문의 효율 향상 및 에너지 수요 감축 노력을 통하여 CCS, 신재생에너지, 기타 저탄소 기술 등 공급 측면의 부담을 완화할 수 있을 것으로 기대함

❑ EU 및 독일의 에너지 수요 관련 정책 동향

- o 유럽은 러시아-우크라이나 전쟁 등 에너지 공급 및 수입의 안정적인 유지, EU 기후목표 달성 가속화, 에너지 가격 변동성에 대응하기 위하여 에너지 소비 측면의 정책을 적극적으로 활용하고 있음
- o “REPowerEU”의 일환으로 “EU Save Energy Plan”을 제안하여 EU 내 에너지 소비 절감을 지원하고 있음
  - 해당 계획은 더 많은 대중 교통과 효율적인 가전제품 제공을 지원하며, 냉방기기의 사용을 줄이도록 장려하고 있음
  - 건물의 에너지 성능 및 에너지 감사에 대하여 보다 강화된 규정이 포함되어 있음
- o “2030 Energy Efficiency Directive”는 2030년까지 2020년 기준 시나리오 대비 에너지 수요를 11.7% 추가로 감축하기 위하여 강화된 에너지 효율 목표를 제시하였음
  - 해당 Directive는 2030년까지 1차에너지 소비와 최종에너지 소비를 각각 40.5%, 38%

감축하는 것을 목표로 설정하였음

- EU 회원국이 에너지 소비에 영향을 미치는 국가별 상황을 고려하여 객관적으로 에너지 집약도 및 에너지 소비 절감 등 자체적인 목표를 설정하도록 제안하고 있음

- o 개정된 “Energy Efficiency Directive”의 “Energy Efficiency First” 원칙은 에너지 효율 향상과 생산 비용 절감을 우선시하는 정책 및 투자 결정의 법적 근거를 마련하고 있음
  - “Energy Efficiency First” 원칙은 (1) 에너지 수요 절감을 통하여 신재생에너지로의 전환에 필요한 투자 수준을 낮추며, (2) 제한된 자원의 지속가능한 사용을 지원하고, (3) EU 에너지 시스템의 탄력성을 높일 수 있음

〈표 1〉 EU 법안 내 “Energy Efficiency Principle”

요구사항	주요 내용
요구사항 1	- 에너지 효율 조치의 장점에 대한 평가를 포함하여 비용-편익 평가 방법론 적용
요구사항 2	- 원칙의 적용을 모니터링 할 책임이 있는 주체 식별
요구사항 3	- 위원회(Commisssion)에 원칙의 적용에 대해 보고

자료: European Commission(2023.12.24), “Energy Efficiency First Principle”, 검색일: 2024.1.11.

- o 독일은 에너지 전환과 기후변화 대응을 위해 EU의 목표보다 장기적이며 상당한 에너지 수요 절감을 추진하고 있음
  - “New Energy Efficiency Act”를 통하여 공공 및 민간 부문의 장기 에너지 소비 절감 목표를 2030년까지 2008년 대비 26.5% 감축하도록 설정하고 있음
  - 연간 15 GWh 이상 에너지를 소비하는 기업은 에너지 또는 환경 경영 시스템 구축이 의무화됨
  - 독일의 “2023 Climate Action Program”에는 다양한 에너지 효율 향상 및 에너지 소비 조치들이 포함되어 있음

3. 글로벌 CGE 모형 개발 및 개선

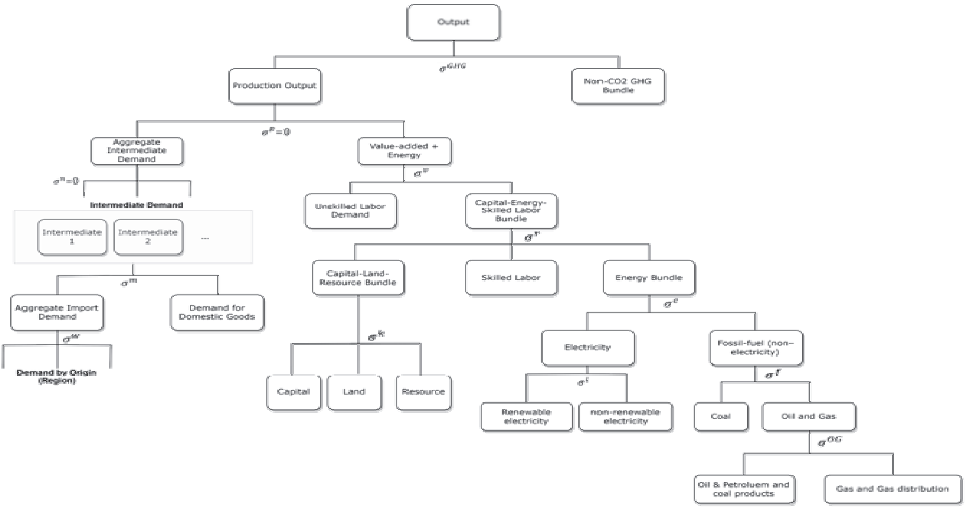
□ 글로벌 CGE 모형 구조

- o 글로벌 CGE 모형은 12개 전력 기술에 상세한 정보를 포함한 76개 부문과 160개 지역

및 국가를 포괄하는 최신 GTAP 11 Power 데이터베이스를 활용하고 있음

- o 본 연구에서는 전체 데이터베이스의 76개 부문을 21개 부문으로 구성하였으며, 160개 지역을 17개 지역 및 국가로 구분하였음
- o 글로벌 CGE 모형은 6가지 주요 온실가스 (N_2O, CH_4, NF_3, SF_6, PFCs, HFCs)를 포함하고 있으며, 보정(calibration)을 위해 EU Navitage 프로젝트의 업데이트된 SSP2 시나리오를 적용하였음
- o 해당 모형은 대체탄력성이 다르게 적용된 ‘구(old)자본’과 ‘신규(new)자본’을 구분하였으며, 신규 자본은 보다 유연하게 부문 간 대체가 가능하도록 설정되었음

〈그림 2〉 모형의 생산 구조



자료: 저자 작성.

❑ 기후 모듈의 개발과 냉난방 에너지 수요 변화를 위한 피해함수 적용

- o 글로벌 및 지역별 기온 변화에 따른 에너지 소비량 변화를 분석하기 위하여 통합평가모형인 FUND 모형의 기후 모듈을 도입하였음
  - FUND 모형의 기후 모듈은 대기 중 이산화탄소 농도, 복사 강제력(radiative forcing), 지구 평균 기온 변화를 계산할 수 있음
  - 글로벌 CGE 모형에서 6대 온실가스 배출량을 계산하고, 이 정보를 기후 모듈에 반영하여 글로벌 평균 기온 상승을 계산함

- o 기후변화가 에너지 수요에 미치는 영향을 분석하기 위해 FUND 모형의 냉난방 에너지 소비 변화에 대한 피해함수를 모형에 적용하였음
  - 기후 모듈에서 글로벌 평균 기온 변화를 계산하며, CGE모형에 적용된 피해함수를 통해 기온 변화에 따른 냉난방 에너지 수요 변화를 계산함
- o 이를 통해 계산된 냉난방 에너지 수요 변화는 CGE 모형의 에너지-자본-숙련된 노동력 번들의 비중을 조정하도록 설정되어 반영되었음

□ 가구의 에너지 소비 제약 적용

- o 가구 에너지 소비 제약을 반영하기 위해 전력 및 에너지 번들의 비중 파라미터를 조정하는 방식을 적용하였음
  - 비중 파라미터는 일정한 수준으로 변하도록 가정하였으며, 선진국(Global North) 지역은 매년 1.5%, 개발도상국(Global South) 지역은 매년 1.25%씩 에너지 소비가 줄어드는 것으로 가정하였음
  - 본 연구는 Grubler et al.(2018)의 소비 관련 활동과 에너지 소비 변화를 고려하여, 선진국 지역의 가구 에너지 소비 절감이 상대적으로 높게 일어날 것이라고 가정하였음

4. 저에너지 수요 시나리오 구성

□ 저에너지 수요 시나리오의 주요 구성요소

- o 선행연구 분석과 글로벌 CGE 모형 구조를 고려하여, 본 연구에서는 저에너지 수요 시나리오를 구성하기 위해 5가지의 핵심 구성요소를 선정하였음
  - 5가지 핵심 구성요소는 (1) 산업 및 가구의 에너지 효율 향상, (2) 기후변화에 따른 에너지 수요 변화, (3) 행태 변화, (4) 탄소 가격, (5) COVID-19의 영향임

□ 저에너지 수요 시나리오의 구조 및 가정

- o 지역별 (선진국 및 개발도상국) 다른 에너지 효율 향상이 가정됨
  - 선진국의 에너지 효율 수준이 상대적으로 높으며, 개발도상국의 에너지 효율 개선 잠재력이 크다는 점을 고려하여 개발도상국은 매년 1.5%, 선진국은 매년 1%씩 에너지 효율이 향상되도록 가정하였음
- o 자본-에너지-숙련된 노동력(KTRE) 번들에는 FUND 모형의 피해함수로부터 산출된 냉난방 에너시 소비 변화가 적용됨
  - 글로벌 CGE 모형에 적용된 기후 모듈과 냉난방 에너지 소비의 피해함수를 활용하여

기온 상승에 따른 냉난방 관련 추가적인 에너지 지출액을 산출함

- o 신재생에너지 보급에 따른 전력화를 고려하였음
  - 모형 내에서 신재생에너지의 보급에 따른 학습효과를 적용함으로써, 신재생에너지로의 에너지 전환 가속화를 간접적으로 반영하였음
- o 가구의 에너지 소비 절감에 대한 외생적인 제약조건이 적용됨
  - 본 연구의 저수요 시나리오는 선진국과 개발도상국의 가구가 각각 연간 1.5%, 1%씩 에너지 소비를 절감하는 외생적인 제약조건을 적용하여, 사람과 가구의 행태변화를 반영하였음
- o 본 연구에서는 NGFS Phase 4의 Net Zero 2050 시나리오 (REMIND-MAgPIE 모형)의 탄소가격을 가져와 외생적으로 반영하였음
  - 글로벌 CGE 모형에서는 DAC, CCS, 수소 등 신기술·신산업이 적용되어 있지 않아, 직접적으로 탄소중립을 분석하는데는 한계가 있음
  - 탄소배출량을 제약하는 시나리오를 설정하는 대신, 본 연구의 시나리오 분석에서는 NGFS Phase 4 Net Zero 시나리오의 2030, 2040, 2050년 탄소가격을 고려하여 분석하였음

❑ 시나리오 설정

- o 저에너지 수요 분석을 위하여 기준 시나리오(BAU), 에너지 지출 포함 BAU(E_EXP), 산업부문 저에너지 수요(LED_ind), 탄소가격 시나리오(NZ), 탄소가격 하 산업부문 저에너지 수요(LED_ind_NZ), 저에너지 수요 시나리오(LED_all_NZ)를 구성하였음
  - 기준 시나리오(BAU)는 업데이트 된 SSP2 시나리오를 따라 경제가 성장하는 것을 가정하였음
  - 에너지 지출 포함 BAU(E_EXP) 시나리오는 BAU 시나리오에 기온 상승에 따른 냉난방 에너지 수요 변화를 반영한 시나리오임
  - 산업부문 저에너지 수요(LED_ind) 시나리오는 E_EXP 시나리오에 산업 부문의 에너지 효율 향상이 반영된 시나리오임
  - 탄소가격 시나리오(NZ)는 E_EXP 시나리오에 NGFS Net Zero 2050의 탄소가격이 적용된 시나리오임
  - 탄소가격 하 산업부문 저에너지 수요(LED_ind_NZ) 시나리오는 탄소가격 시나리오의 배출 경로를 따라가는 가운데, 추가적으로 산업 부문의 에너지 효율 향상을 고려한 시나리오임
  - 저에너지 수요 시나리오(LED_all_NZ)는 탄소가격 시나리오의 배출 경로를 따라가는 가운데 산업과 가구의 에너지 효율 향상과 가구의 에너지 소비 제약이 모두 반영된 시나리오임

5. 결과 및 정책적 시사점

❑ 분석 결과: 글로벌

o 기온 상승과 에너지 효율 개선은 에너지 수요와 온실가스 배출을 증가시키는 영향을 가져올 수 있음

- 상당한 탄소 가격 정책이나 감축 조치가 없을 경우, 향후 수십 년 이내에 지구 평균 기온 상승이 2℃를 넘어설 수 있음
- 지구 평균 기온 상승은 냉난방 에너지 수요가 일부 증가시킬 것이라고 예상됨
- E_EXP 시나리오에서 산업 부문의 에너지 효율 개선은 최종에너지 수요를 BAU 대비 증가시킨다는 점에서 선행연구와 유사하게 에너지 효율 향상의 리바운드 효과가 발생하였음

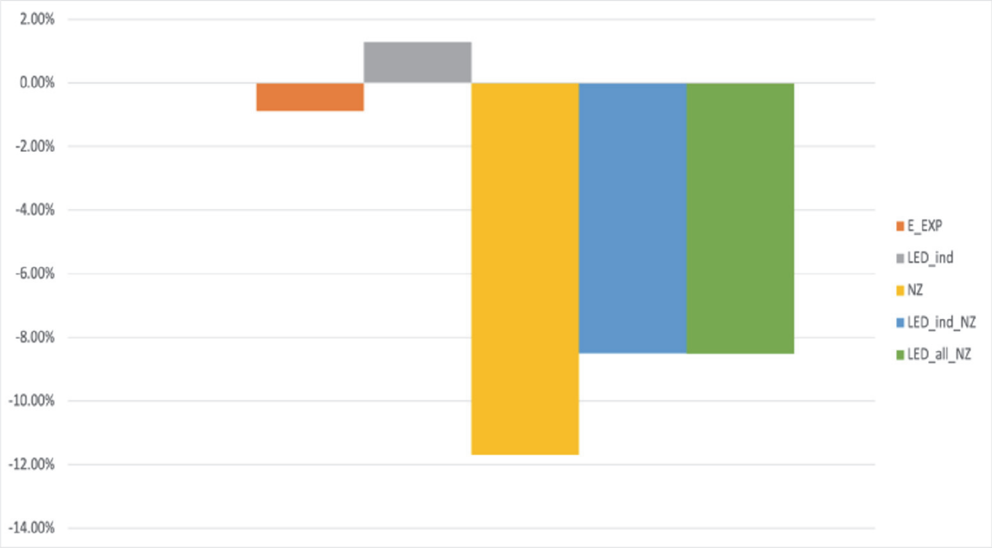
o 탄소가격 시나리오(NZ)에서는 탄소가격의 도입이 온실가스 배출량과 최종에너지 수요를 크게 줄이는 것으로 나타났으나, 동시에 상당한 경제적 손실도 초래할 수 있음

- NZ 시나리오는 2021~2050년 기간 BAU 수준 대비 약 11.7%의 GDP 손실을 초래할 수 있음
- 석탄과 가스 등 화석연료 부문은 상당히 부정적인 경제적 영향을 받을 수 받을 수 있으며, 생산량은 BAU 대비 약 38-59% (2021-2050) 감소할 수 있음

o 탄소가격이 도입되면, 산업 및 가구의 에너지 효율 개선과 가구 에너지 소비 절감은 최종에너지 소비를 추가로 줄일 수 있을 뿐 아니라 온실가스 감축에 따른 경제적 부담을 줄이는데도 기여할 수 있음

- 탄소가격과 함께 에너지 효율 개선과 가구 에너지 소비 절감을 위한 노력이 수반되면 최종에너지 수요가 BAU에 비해 30% 이상 줄일 수 있는 것으로 나타남
- 탄소가격만 적용될 경우, 글로벌 GDP 손실은 BAU 대비 11% 이상이 될 수 있으나, 저에너지 수요 수단을 도입하면 글로벌 GDP 손실은 BAU 대비 8.5% 수준으로 낮아질 수 있음
- 저에너지 수요 수단들은 탄소가격 시나리오에 비해 비화석연료 관련 부문의 생산 및 투자에 일반적으로 더 나은 결과를 가져올 수 있음

〈그림 3〉 글로벌 실질 GDP 변화 (2021-2050) (BAU 대비 %)



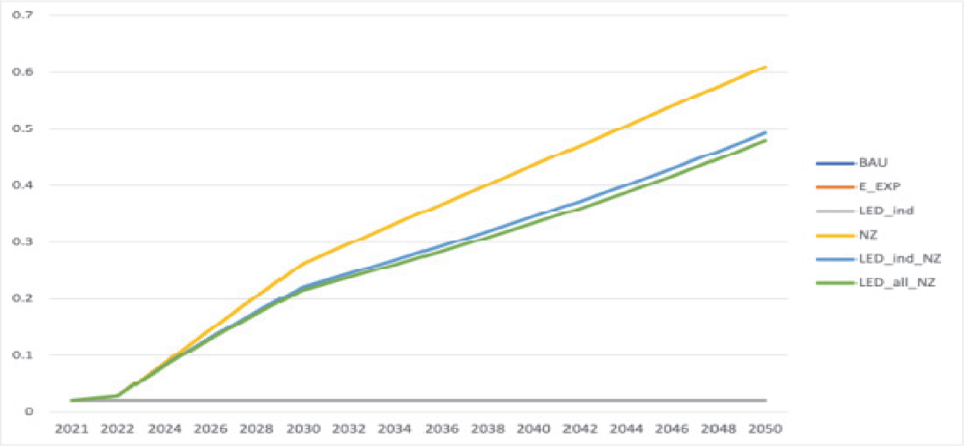
자료: 저자 작성.

□ 분석 결과: 한국

- ㅇ 글로벌 기온 상승은 국내 냉난방 에너지 수요를 다소 증가시킬 수 있으나, 온실가스 배출 상승에 미치는 영향은 크지 않음
- ㅇ 글로벌 결과와 유사하게, 저에너지 수요 수단들은 온실가스 감축이 가져올 수 있는 부정적인 경제적 영향을 줄일 수 있음
  - 저에너지 수요 수단이 고려된다면, 탄소가격 시나리오(NZ)와 동일한 온실가스 감축 수준을 달성하는데 필요한 경제 전반의 탄소가격 수준을 낮출 수 있음
  - 탄소가격 시나리오는 2050년 tCO_2eq 당 610달러이나, LED_all_NZ 시나리오에서는 동일한 온실가스 배출 감축을 달성하기 위해 tCO_2eq 당 480달러만 필요한 것으로 나타남

〈그림 4〉 시나리오 별 탄소가격 경로 (2021-2050)

(단위: 천 달러)



자료: 저자 작성.

- 탄소가격 도입은 2021-2050년 기간 동안 실질 GDP를 BAU 대비 6.88% 낮출 수 있으나, 저에너지 수요 수단이 적용된다면 동일 기간동안 실질 GDP 손실은 BAU 대비 1.86-1.92% 수준으로 낮아질 수 있음

o 부문별 생산의 경우, 탄소가격이 도입되면, 신재생에너지와 원자력 생산은 크게 증가하지만 화석연료 관련 부문의 생산은 감소할 것으로 나타남

- 시나리오 분석 결과에서 글로벌 결과와는 달리 한국은 재생에너지 생산 증가에 비해 원자력 발전의 증가 비중이 상대적으로 크게 나타남
- 탄소가격에 저에너지 수요 수단이 같이 도입된다면, 비에너지 관련 산업 부문의 생산 및 투자 손실을 낮출 수 있음

❑ 민감도 분석 결과

o 저에너지 수요 수단의 잠재력을 살펴보기 위해 보다 가속화된 수요 절감이 이뤄질 때를 가정한 두 가지 시나리오를 추가하여 민감도 분석을 수행하였음

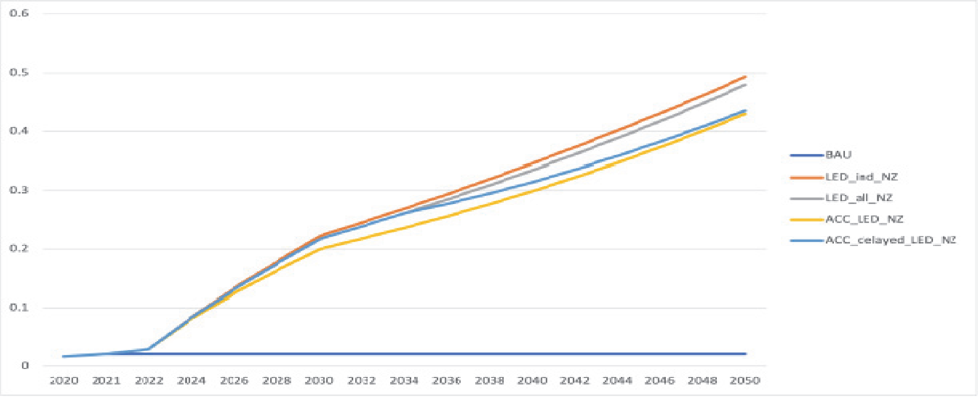
- 가속화된 산업 에너지 효율 시나리오(ACC_ind_NZ)는 산업 및 가구의 에너지 효율 개선 노력이 강화되어 개발도상국에서 연간 1.75%, 선진국에서 1.5%로 기존보다 더 빠르게 일어남을 가정하고 있음
- 가속화된 저에너지 수요 시나리오(ACC_LED_NZ)는 산업 및 가구의 에너지 효율 개선 노력에 추가적으로 가구의 에너지 소비 절감 노력이 강화되는 것을 나타냄

가구 에너지 소비 절감은 개발도상국에서 연간 1.5%, 선진국에서 1.75%로 더 빠르게 일어남을 가정함

- o 가속화된 저에너지 수요 시나리오들은 글로벌 에너지 수요를 더 크게 줄이고, 탄소가격 도입에 따른 GDP 손실을 줄일 수 있음
  - 가속화된 수요 시나리오들은 기존 저에너지 수요 시나리오에 비해 최종에너지 수요와 GDP 손실을 줄이는 것으로 나타남. 이들 시나리오의 GDP 손실 (2021-2050)은 BAU 수준 대비 7~8% 수준으로 기존 저에너지 수요 시나리오(LED_all_NZ)의 8.5%에 비해 적은 수준임
  - 가속화된 수요 시나리오들의 전세계 생산 및 투자 추세는 기존 저에너지 수요 시나리오와 일반적으로 유사한 모습을 보이나, 글로벌 생산 및 투자 손실은 기존 저에너지 수요 시나리오에 비해 소폭 감소하는 것으로 나타남
- o 한국의 경우, 가속화된 시나리오들은 기존 저에너지 수요 시나리오에 비해 상당한 경제적인 효과를 가져다주는 것으로 나타남
  - 가속화된 수요 시나리오들에서 탄소가격 시나리오의 배출 경로를 따르기 위해 필요한 탄소 가격은 기존 저에너지 수요 시나리오에 비해 낮아지는 것으로 나타남
  - 2050년 탄소가격은 기존 탄소가격 시나리오 하에서 tCO_2eq 당 610달러, 기존 저에너지 수요 시나리오 하에서 tCO_2eq 당 480달러이었음. 가속화된 수요 시나리오 하에서는 동일한 온실가스 감축을 달성하기 위하여 2050년 탄소가격이 tCO_2eq 당 430-435 달러로 낮아지는 것으로 나타남

〈그림 5〉 탄소가격 비교 (기존과 가속화된 수요 시나리오 비교)

(단위: 천 달러)



자료: 저자 작성.

- 한국에서 가속화된 수요 시나리오들은 기존 저에너지 수요 시나리오에 비해 생산과 투자에 긍정적인 영향을 가져올 수 있을 것으로 나타남
- 부문별로 살펴보면, 가속화된 수요 시나리오들은 기존 저에너지 수요 시나리오에 비해 여러 비에너지 부문의 생산을 소폭 증가시키는 것으로 나타났음

□ 정책적 시사점

- o 글로벌 기온 상승은 온실가스 배출량과 최종에너지 수요를 다소 증가시킬 수 있으나, 그 영향은 지역별로 상의함
- o 탄소가격을 동반한 에너지 수요 저감 수단들은 시너지 효과를 가져와 보다 효율적이며 효과적으로 온실가스 감축을 달성할 수 있도록 지원함
  - 탄소가격 없이, 에너지 효율 개선과 가구의 에너지 소비 절감만으로는 온실가스 감축 및 최종에너지 수요 절감에 제한적인 영향만 있음
- o 에너지 사용과 온실가스 배출이 많은 산업 부문의 전환은 에너지 수요 저감과 탄소중립 달성을 위한 전환의 필수적인 부분임
  - 본 연구는 산업 부문의 에너지 효율 개선이 탄소중립 전환을 지원하며, 저수요를 달성하는데 기여할 수 있는 잠재력에 대한 근거를 일부 제시할 수 있음
  - 설계 변화, 순환 경제, 탈물질화(dematerilization), 기술 발전과 같은 수단을 고려한다면, 저에너지 수요 수단들은 보다 상당한 긍정적인 영향을 가져올 수 있음
  - 혁신적인 기술과 산업을 지원하는 것은 긍정적인 경제적 성과로 이어질 수 있음
- o 저에너지 수요로의 전환은 정의로운 전환 측면에서도 긍정적인 영향을 제시할 수 있음
  - 에너지 수요를 낮추는 수단들은 예상되는 경제적 손실을 줄이며, 사회의 경제적 부담을 줄이는데 기여할 수 있음
  - 저소득층 혹은 취약계층을 지원하기 위해 탄소 수입(carbon revenue)을 활용하게 된다면 탄소중립을 지원할 수 있음. 탄소가격제에 따른 수입을 활용하는 정책 및 전략은 전환 경로에서의 사회적 비용을 완화할 수 있도록 설계되어야 함
  - 에너지 소비를 줄이며, 저수요 생활양식을 채택하는 것은 에너지 지출을 줄여 가구의 경제적 부담을 완화할 수 있음
- o 향후 연구로는 주로 현재의 글로벌 CGE 모형을 개선하고, 데이터베이스의 활용 및 관리의 개선이 필요함
  - 상세한 탄소중립 분석을 위해서는 CCS, DAC, 수소와 같은 혁신적인 저탄소 기술들이 모형에 포함되어야 함
  - 개별 혹은 여러 수요측면의 수단과 그들의 경제 전반에 걸친 잠재력을 모두 다루기

위해서는 MESSAGEix, GCAM, REMIND 모형과 같은 상·하향식 통합모형이 필요함

- 투명하고 표준화된 데이터베이스 관리는 다른 연구기관 및 연구 커뮤니티와의 협업을 촉진할 수 있음
- 실시간 에너지 소비 데이터, 에너지 소비의 사회 및 경제적 동인과 같은 개인 및 가구의 행태 정보를 수집하는 것이 보다 중요해질 것임

□ 에너지 수요 관련 잠재적인 연구 주제

- ο 순환경제, 자원 순환과 이들이 에너지 수요에 미치는 영향
  - 최근 산업 에너지와 자원 수요 및 생산 간 연계를 가능하게 하는 MESSAGEix-Materials가 MESSAGEix-GLOBIOM 프레임워크에 포함되었음
  - 미래 전환 과정에서 순환경제의 중요성이 높아짐에 따라, 순환경제 수단들과 긴밀하게 연계된 통합평가모형(IAM) 시나리오 구축에 대한 요구가 높아질 수 있음
  - 순환경제 수단들을 분석하기 위해 글로벌 CGE 모형을 더욱 발전시켜나가는 것이 필요하며, MESSAGEix의 상세한 자원 관련 변수들을 고려하는 것이 가능함
- ο 기존 수요 내러티브와의 연계
  - 여러 모델링 팀들이 ASI(회피-전환-개선) 프레임워크에 따른 수요 변화 내러티브를 중심으로 시나리오를 구성하고 있으며, MESSAGEix는 보다 상세한 수요 모듈을 기반으로 한 시나리오들을 보유하고 있음
  - 시나리오의 상향식(bottom-up) 특성을 고려할 때, 기존의 수요 내러티브는 각 부문의 전환에 더 많은 인사이트를 제시할 수 있음
- ο 정의로운 전환과 고용 및 기타 웰빙 지표에 미치는 영향 분석
  - 웰빙 문제의 다차원(multidimensionality)적인 측면을 고려할 때, 최근 연구들은 수요에 초점을 맞춘 전환이 신중히 실행된다면 웰빙에 긍정적일 수 있다고 보고 있음
  - CGE 기반 모형들은 MESSAGEix와 같은 프로세스 기반 통합평가모형이 볼 수 없는 감축 혹은 수요에 초점을 맞춘 전환 시나리오가 가져오는 경제 전반의 영향에 대한 인사이트를 제시할 수 있음
  - IIASA의 최근 프로젝트인 “Just Transition for All”은 감축 시나리오의 웰빙 평가를 위한 추가적인 지표들을 개발하고 있음

6. 결 론

❑ 연구의 주요 시사점

- o 저에너지 수요 시나리오 논의 및 모델 개발 동향을 파악함
- o 본 연구는 글로벌 기온 상승에 따른 에너지 수요 영향과 저에너지 수요 시나리오의 경제적 영향을 분석하기 위해 글로벌 CGE 모형을 개선함
  - 많은 선행연구에서 활동 수준이나 개입에 따른 영향을 분석하는 반면, 저에너지 수요 시나리오의 전반적인 경제적 영향에 대한 분석은 많이 이뤄지지 않음
- o 본 연구는 수요 효율화, 에너지 수요 대책에 대한 범국민적인 인식제고 등 국내 수요 관련 정책 수립 및 확산을 위한 근거를 제공하는데 기여할 수 있음

❑ 저에너지 수요 시나리오 분석의 시사점

- o 탄소가격 도입은 GDP와 산업 생산 및 투자에 부정적인 경제적 영향을 가져올 수 있으며, 특히 화석연료 관련 부문에 부정적인 영향을 가져옴
- o 산업 간 상당한 전환이 이뤄질 수 있으며, 이러한 전환을 촉진하기 위한 정책 요구가 강조될 것임. 정의로운 전환에 대한 관심을 제고하고, 전환을 가속화하기 위한 기술 및 정책의 개발이 필요함
  - 기존 화석연료 기반 혹은 에너지 집약적인 산업의 생산과 투자가 감소함에 따라 일자리 손실과 좌초자산 증가가 발생할 것임
  - 재교육 프로그램, 좌초자산을 줄이기 위한 정책, 화석연료, 에너지 및 배출 집약적인 산업 주변의 지역 경제 지원 등과 같은 상당한 정책 대응이 필요할 것임
- o 전환에 따른 경제적 부담을 줄일 수 있는 에너지 수요 관련 정책의 필요성이 강조될 필요성이 있음
  - 탄소가격과 더불어 저에너지 수요 수단들이 도입된다면 동일한 수준의 배출량 감축을 달성하는데 필요한 탄소 가격을 낮출 수 있음
  - 저에너지 수요 수단들은 실질 GDP 뿐 아니라 비에너지 부문의 생산 및 투자에도 긍정적인 영향을 가져올 수 있음
- o 에너지 수요 정책은 탄소중립으로의 전환에 따른 사회경제적 영향을 줄일 수 있을 뿐 아니라 공급 측면의 부담을 줄이는 데도 기여할 수 있는 잠재력이 있음
  - 에너지 수요 감소에 산업 부문의 에너지 효율 향상이 크게 기여하다는 결과는 에너지 효율 향상 노력을 지속해야 할 필요성을 강조함
  - EU Energy Efficiency First Principle과 같이 에너지 수요 또는 에너지 시스템에

영향을 미치는 부문에 대한 정책 및 투자 결정에 명시적으로 에너지 효율을 높이기 위한 노력 및 조치를 반영하는 원칙을 도입 혹은 설계하는 것을 고려할 수 있음

- 혁신적 기술의 채택을 지원하는 것이 중요함
- 에너지 소비를 줄이기 위한 행태 변화를 촉진하는 정책이나 초기부터 에너지 소비를 줄일 수 있도록 도시를 설계하는 정책 등을 고려할 수 있음

o 저에너지 수요 시나리오에 대한 보다 종합적인 분석을 위해서는 모형의 추가적인 개발이 필요함

- 본 연구에서 활용된 모형의 구조적 한계와 제한된 범위의 저에너지 수요 수단은 향후 연구를 통해 해결해야 하는 과제임
- 탄소중립 전환을 분석하기 위해서는 CCS, 수소 등 혁신 기술과 순환경제 및 자원 수요 등을 모형 내에 포함시켜야 함
- 글로벌 CGE 모형과 부문별 모형 간 연계를 통해 개별 혹은 여러 저에너지 수요 수단들을 모형에 보다 상세하게 반영할 수 있을 것임

o 저에너지 수요 분석을 보다 활발히 하며, 모형을 효율적이며 효과적으로 고도화하기 위해서는 모델링 및 시나리오 분석에 대한 노하우와 전문성을 보유한 국제 연구기관과의 연구협력이 필요함

주제어: CGE 모형, 에너지 수요, 시나리오 분석, 국제 연구협력, 모델링

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Major Publications

- Understanding the Characteristics of Residential Electricity Consumption in Korea (2023)
- Why the Republic of Korea, Taiwan and Singapore Coped Well with COVID-19 and What are the Lessons Learned from Their Experiences (2022)
- A Critical Review of Korea's Long-term Contract for Renewable Energy Auctions (2020)

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Analysis of Low-Energy Demand Scenarios with Global CGE Model

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93530
ISBN 979-11-5980-936-1