

Development of a National Long Term Energy Mix Optimization Model for Achieving Carbon Neutrality by 2050

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1. Introduction

As part of a project of the Energy Special Committee of the Korean Nuclear Society, researchers from the Department of Nuclear and Quantum Engineering at KAIST, the Nuclear Policy Center at Seoul National University, and the Policy Research Department at the KAERI are collaborating to develop a long term national energy mix model to support South Korea's 2050 carbon neutrality goal.

To provide a quantitative basis for assessing the role of nuclear power in the long term energy mix, a national long term energy mix optimization model has been developed based on the '11th Basic Plan for Long-Term Electricity Supply and Demand(11th Basic Plan)'. In accordance with Article 25 of the Electricity Business Act, the 11th Basic Plan, announced in 2025, presents electricity demand and supply projections, the power generation mix, and capacity expansion plans through 2038. However, the pathway toward 2050 beyond the planning horizon of the 11th Basic Plan has yet to be established. The model developed in this study is used to analyze alternative energy mix scenarios for the period from 2039 to 2050, with a particular focus on the share of nuclear power, and representative results of the scenario analyses are presented.

2. Methods and Results

In this section, the 11th Basic Plan is analyzed and evaluated, and the structure and development methodology of the model developed to derive the future national energy mix based on the plan are described. In addition, three scenarios are developed to compare projected electricity generation and generation capacity across the scenarios, and the total system cost is estimated to assess the economic implications of each scenario.

2.1 Analysis of 11th Basic Plan for Long-Term Electricity Supply and Demand

The 11th Basic Plan projects that electricity consumption and peak electricity demand will increase at average annual rates of 0.9% and 1.8%, respectively, from 2024 to 2038, based on the target demand scenario. Since peak demand is expected to grow at a faster rate

than electricity consumption, the overall load factor of the power system is projected to gradually decline. Taking into account a reserve margin of 22%, the required generation capacity is estimated to reach approximately 158 GW by 2038. After accounting for the effective capacity of committed dispatchable and renewable power plants, an additional 10.3 GW of new capacity is expected to be required. This additional capacity is planned to be supplied through a combination of nuclear power, combined heat and power (CHP), and other carbon free generation sources.

In terms of the generation mix, the share of carbon-emitting generation, which accounted for approximately 61% of total generation in 2023, is projected to decline to 29% by 2038. In contrast, carbon-free generation, including nuclear power, renewables, clean hydrogen, and clean ammonia, is expected to account for approximately 70% of total generation by 2038. In particular, the share of nuclear power is projected to increase from 30.7% to 35.2%, while the combined share of renewables and new energy is expected to increase from 9.6% to 33.0%, representing an approximately 3.4fold increase.

At the same time, the increasing penetration of renewables is expected to increase variability in the balance between electricity supply and demand and raise the need for enhanced frequency stability. Accordingly, the expansion of grid-stabilizing and flexible resources is considered essential. Pumped storage and energy storage systems are therefore projected to reach a combined capacity of approximately 23 GW by 2038. Nuclear power is expected to play an increasingly important role as a carbon-free baseload generation source, while the commercialization of small modular reactors (SMRs) in South Korea is planned by 2035.

2.2 Energy System Modeling Using MESSAGE

This study utilized MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts), a long term energy planning model developed by IIASA and distributed/managed by the IAEA. As a core driver of global Integrated Assessment Models (IAMs) such as those in IPCC report, MESSAGE possesses four key characteristics:

1. Cost Optimization Structure: A Linear Programming (LP) model that minimizes Total

Discounted System Cost under given energy demand and operational constraints.

2. Long Term Time Horizon: Models long-term energy transition pathways over 50 years horizon based on annual load patterns.
3. Reference Energy System (RES) Implementation: Rigorously represents the entire supply chain from primary resource extraction to conversion, transport, and end-use demand as a network.
4. Explicit Constraints Application: Explicitly incorporates CO₂ emission caps, technology diffusion rates, and policy mandates as mathematical constraints.

Electricity demand was modeled by synthesizing the 11th Basic Plan and the "2050 Carbon Neutrality Scenarios (Oct. 2021)." The national 2050 scenarios aim for net-zero emissions by 2050 and are categorized into Scenario A (complete phase-out of thermal power) and Scenario B (allowing residual LNG power generation via Carbon Capture, Utilization, and Storage CCUS).

This study adopted Scenario B as the baseline path (Base case). In linear optimization models like MESSAGE, imposing a zero-emission constraint on the power sector can introduce extreme rigidity, leading to infeasibility or overestimation of marginal abatement costs. Incorporating residual CCUS equipped LNG generation provides constraint relaxation and yields a smoother marginal cost transition curve.

Applying transmission/distribution losses (3.6%) and internal station use (3.7%) to Scenario B's projected 2050 total generation (1,208.8 TWh) results in a final electricity demand of 1,123.3 TWh. This corresponds to a CAGR of approximately 5% from 2039 to 2050.

To capture daily/seasonal demand variations and renewable (solar/wind) output profiles while avoiding excessive computational burden from modeling 8,760 hourly profiles directly, the power load was aggregated into 140 representative load regions. Based on 2023 hourly demand data from the Korea Power Exchange (KPX) and generation profiles from representative plants (Yeongam Solar and Hankyeong Wind), the model achieved high accuracy, displaying a Mean Absolute Percentage Error (MAPE) of ~5%. Furthermore, declining load factor trends were incorporated, assuming system load factors drop from 68% in 2023 to 65% in 2030, 58% in 2040, and 53% in 2050.

The model incorporates 7 resource types, 29 power technologies (categorized into existing/new facilities), and 4 storage technologies (pumped storage and battery ESS). Outer loop estimations of surplus generation rates from high renewable penetration were fed back into the model to reflect storage operation mechanisms. Technology cost inputs were derived from OECD/NEA's *Projected Costs of Generating Electricity (2020)* and NREL's *Annual Technology Baseline (2025)*. Emission constraints follow a linear trajectory through the 2035 NDC target midpoint (79.2 MtCO₂), reaching a power sector target of 20.7 MtCO₂eq by 2050.

2.3 Scenario Design

Three scenarios were constructed based on the composition between nuclear and renewable energy sources in 2050 (assuming a 5% electricity demand CAGR). Across all scenarios, the combined CFE share (Nuclear + Renewables) was fixed at up to 75%.

Table 1: Summary of Nuclear Share Scenarios (5% Demand CAGR Assumption)

	SC 1	SC 2	SC 3
Share of Nuclear (2050)	10%	35%	50%
Share of RNWs (2050)	65%	40%	25%
LTO	None	20 yrs	20 yrs
New Nuclear (1.4 GW)	0 units	24 units	42 units

- Scenario 1 (Nuclear Stagnation/Minimization): No new nuclear construction and no Long-Term Operation (LTO) past the 11th Basic Plan (10% Nuclear, 65% Renewables in 2050).
- Scenario 2 (Nuclear Share Maintenance): Maintaining the 2038 nuclear share (35%) through 2050 with 20-year LTO (35% Nuclear, 40% Renewables in 2050).
- Scenario 3 (Nuclear Share Expansion): Expanding the nuclear share to 50% by 2050 with 20-year LTO (50% Nuclear, 25% Renewables in 2050).

2.4 Results

Across all scenarios, large scale nuclear capacity was dispatched up to its designated model upper limits.

Table 2: 2050 Generation mix and surplus generation from Renewables

	SC 1	SC 2	SC 3
Nuclear (Large)	9%	33%	48%
Renewables	69%	43%	29%
LNG (incl. H2, Co-firing)	11%	18%	18%
ESS (Storage)	7%	2%	0%
Total Generation	1,387 TWh	1,282 TWh	1,251 TWh
Share of surplus generation	19%	9%	5%

As the nuclear share expands (SC1 → SC2 → SC3), the required renewable and ESS shares drop significantly.

Differences in total generation across scenarios (1,387 TWh vs. 1,251 TWh) stem from surplus generation caused by renewable intermittency. Share of surplus generation from renewables decreases substantially from 19% in Scenario 1 to 5% in Scenario 3.

Table 3: Required Installed Capacity in 2050 by Scenario
(Unit: GW)

	SC 1	SC 2	SC 3
Nuclear	18	59.6	84.8
Renewables	582.5	337.2	230.8
Total Installed Capacity	912.3	622.3	505.1

A key finding from the estimated generation capacity results is that even a substantial increase in renewable generation capacity leads to a relatively small reduction in nuclear generation capacity. For example, when transitioning from Scenario 3 to Scenario 1, the renewable generation capacity required to achieve the share of renewable energy increases by 351.7 GW, from 230.8 GW to 582.5 GW. In contrast, the corresponding reduction in nuclear generation capacity is only 66.8 GW, from 84.8 GW to 18.0 GW. This finding suggests that, even under a scenario in which the share of renewable energy is maximized, maintaining sufficient baseload capacity from dispatchable carbon-free sources such as nuclear power remains essential to compensate for the low capacity factors and intermittency of renewable energy and to ensure a stable supply of baseload electricity in a carbon neutral energy system by 2050.

An analysis of the cumulative total system costs from 2025 to 2050 shows that a higher share of nuclear power generation leads to a substantial reduction in overall system costs.

- Scenario 1 (SC1, 10% nuclear): The cumulative total system cost is KRW 4,013 trillion, representing the highest cost among the three scenarios.
- Scenario 2 (SC2, 35% nuclear): The cumulative total system cost is KRW 3,047 trillion, corresponding to a reduction of KRW 966 trillion (24.1%) compared with SC1.
- Scenario 3 (SC3, 50% nuclear): The cumulative total system cost is KRW 2,728 trillion, representing a reduction of KRW 1,285 trillion (32.0%) compared with SC1 and an additional reduction of KRW 319 trillion compared with SC2.

The annual cumulative cost trajectories indicate that the slope of the cost curve for SC1 increases sharply after the mid 2030s, as the costs associated with the expansion of renewable energy capacity, deployment of energy storage systems (ESS), and efficiency losses due to surplus generation become increasingly significant. In contrast, SC2 and SC3, which assume higher shares of

nuclear power, maintain more gradual cost trajectories due to the reduced need for system flexibility resources and the mitigation of costs associated with surplus generation.

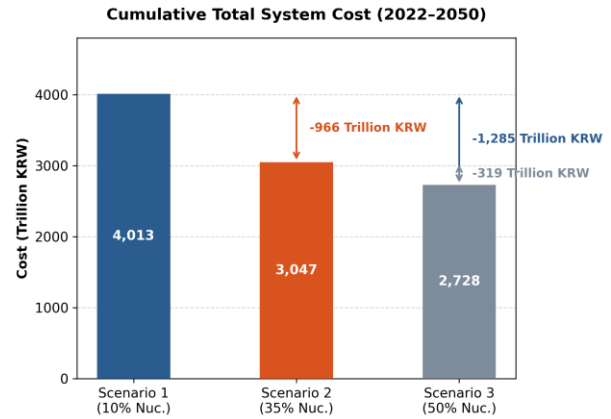


Fig. 1. Cumulative total system cost from 2022 to 2050 across different nuclear generation share scenarios (Base Case: 5% demand CAGR).

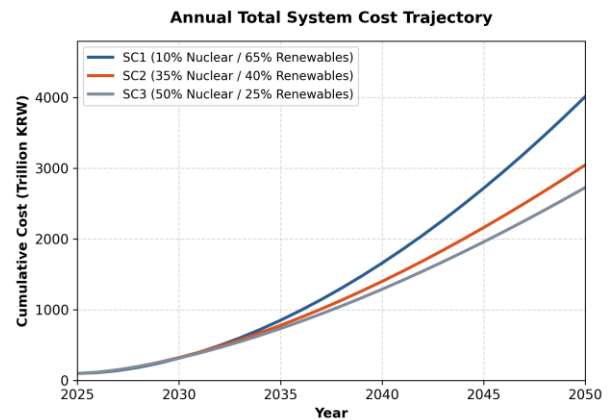


Fig. 2 Annual trajectory of cumulative total system cost from 2025 to 2050 by scenario.

3. Conclusions

This study utilized the MESSAGE linear optimization model to quantitatively derive the optimal long term power mix pathways and economic impacts for achieving 2050 carbon neutrality in South Korea.

The results confirm that maintaining and expanding the nuclear share to 35–50% as a baseload power source reduces grid surplus generation from 19% to 5% and significantly enhances grid stability by preventing system over sizing. Economically, expanding nuclear capacity (SC3) offers a cumulative system cost saving of up to 1,285 trillion KRW (~32%) compared to the renewable-centric path (SC1).

Therefore, achieving national carbon neutrality in a feasible and sustainable manner necessitates a balanced combination of renewable expansion and firm nuclear capacity through new builds and long-term operation

(LTO), serving as a crucial strategy to alleviate national economic burdens during the energy transition.

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