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A Clean Energy Korea by 2035

Transitioning to 80% Carbon-Free Electricity Generation

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ABSTRACT

The current global energy crisis has massive implications for the people and economy of South Korea (Korea), where at least 90% of energy use depends on foreign fossil fuels. Clean electricity accounts for only 39% of total generation, with electricity demand expected to increase 30% by 2035. This study shows that Korea can achieve 80% clean electricity by 2035 by capitalizing on rapid technological improvements and decreasing costs of solar, wind, and battery technology. Doing so would slightly lower electricity supply costs, significantly reduce dependence on imported natural gas and coal, and dramatically cut power sector emissions. Further, this study finds that Korea's power grid under a clean energy scenario will maintain reliability without coal generation or new natural gas plants. To realize these significant economic, environmental, and energy security benefits, policies such as an 80% clean electricity standard by 2035 and corresponding renewable energy deployment goals are required.

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TECHNICAL REVIEW COMMITTEE

Below are the members of the Technical Review Committee (TRC). The TRC provided input and guidance related to study design and evaluation, but, the contents and conclusions of the report, including any errors and omissions, are the sole responsibility of the authors. TRC member affiliations in no way imply that those organizations support or endorse this work in any way.

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EXECUTIVE SUMMARY

The current global energy crisis has massive implications for South Korea (Korea), which depends on foreign fossil fuels for at least 90% of its energy use. At the same time, technological advancements and dramatic cost reductions for solar, wind, and battery storage create significant opportunities to reduce emissions and costs related to Korea's electricity generation, better positioning the country to meet its 2050 goal of carbon neutrality.

The most important decarbonization strategy for Korea is to increase its share of clean electricity generation – primarily from solar- and wind-based renewable energy (RE), but also from nuclear power plants.[1] In 2022, clean generating resources provided only 39% of the country's total electricity generation.

Korea's near-term goal is to reach 59% clean electricity generation by 2036.[2] This study examines the factors involved in hitting associated cost, reliability[3], and emissions targets while dramatically reducing the use of fossil fuels in electricity generation. Further, it aims to inform discussion around Korea's clean energy transition by answering three vital questions:

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[1] Hydrogen is also included as a clean energy source but assessed to have low cost-competitiveness by 2035.

[2] Based on the 10th Basic Plan for Long-term Electricity Supply and Demand.

[3] The term "reliability" refers to the stable, consistent provision of electricity by power systems and has a specific meaning in power system studies. In this study, we matched the hourly operational feasibility of Korea's power system, considering key operational constraints such as ramping limits on thermal power plants, technical minimum generation levels, seasonal and diurnal constraints on hydro dispatch, and constraints on transmission / transfer capacity. We also maintain a minimum planning reserve margin in our capacity expansion modeling, as well as operational reserves (i.e., spinning, load following, and regulation) during the production cost modeling. While our modeling is at an hourly resolution and stops short of a full reliability analysis, it does capture the necessary elements of a reliability analysis and therefore we use the term "reliability" throughout. Moreover, this study's companion policy brief, Korean Power System Challenges and Opportunities: Priorities for Swift and Successful Clean Energy Deployment at Scale, did conduct a full power system reliability analysis addressing characteristics (e.g., inertia, resource adequacy) that are not considered here. All recommendations in both reports are mutually consistent, and none conflict with the policy brief's reliability analysis.

- What effect will recent declines in wind, solar, and battery storage costs have on the pace and scale of renewable resource development?
- What clean energy goals are technically and economically feasible, given inherent uncertainties about electricity demand growth, fossil fuel prices, and RE and energy storage costs?
- How can a faster transition to clean energy deliver not only environmental and economic benefits, but also reduce security risks related to dependence on imported fossil fuels?

This study uses state-of-the-art capacity expansion and hourly dispatch models to explore clean energy deployment in 2025, 2030, and 2035, and considers two main scenarios. The Current Policy scenario limits annual deployment of wind and solar generation to current government goals, reflecting the 2030 nationally determined contribution (NDC) targets, 2050 carbon neutrality goal, and 10th Basic Plan for Long-term Electricity Supply and Demand (10th Basic Plan[4]). The Clean Energy scenario increases annual deployment of wind and solar generation to the maximum feasible levels assumed in this study, which are determined by our modeling and may exceed existing goals. We also applied multiple sensitivity analyses to the Clean Energy scenario (e.g., high and low RE and storage costs, high fossil fuel prices, and grid reliability).

Our findings show that **Korea can cost-effectively deploy an additional 43 GW of renewable energy by 2035** beyond Current Policy requirements – a 31% increase in RE capacity deployed – in a way that maintains a reliable electricity grid. Accordingly, we recommend that Korea increase its 2035 deployment goals for RE and energy storage to realize significant economic, energy security, and environmental benefits while accelerating progress toward carbon neutrality and combatting climate change.

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[4] Korea's comprehensive documentation of electricity regulations and plans, which includes the basic principles of electricity supply and demand, long-term forecasts, power system planning, and demand-side management. The Basic Plan is updated every two years, most recently in January 2023, covering the period of 2022-2036.

KEY FINDINGS

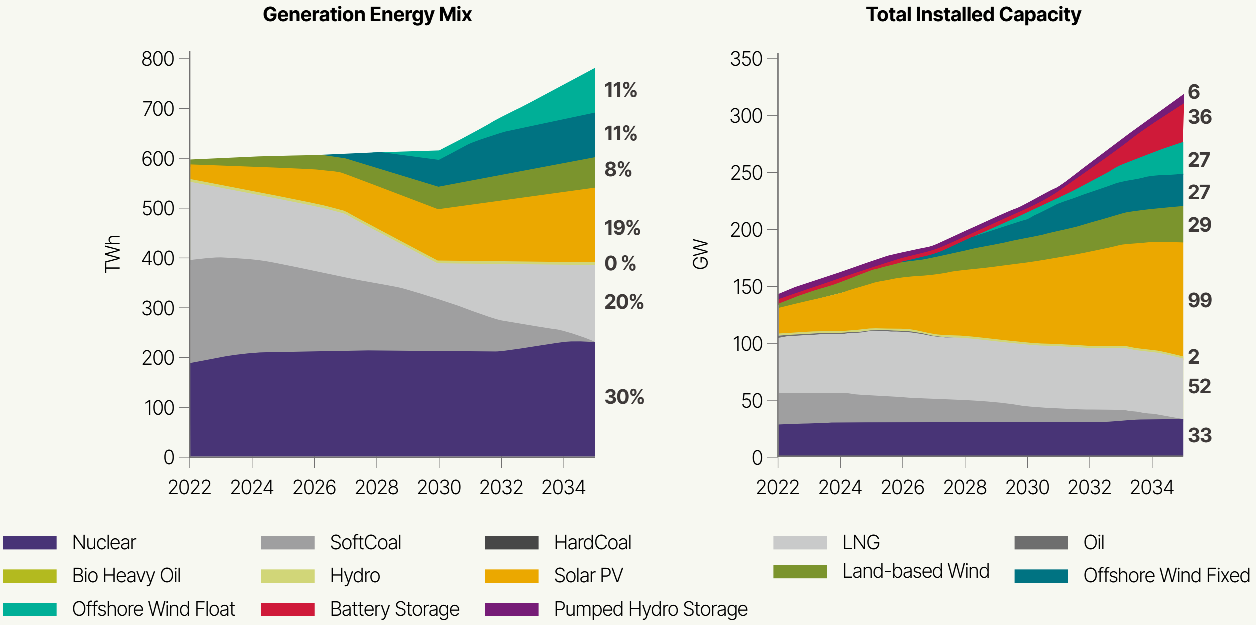
Korea's 80% Clean Grid by 2035 is Reliable Without Coal Generation or New Natural Gas Plants

There has been a longstanding debate about whether Korea could reliably operate electricity systems with high penetrations of RE generation. This study finds that in the Clean Energy scenario, land-based wind, offshore wind, and solar photovoltaic (PV) provide half of electricity generation by 2035, while nuclear power provides 30% for a total of 80% non-fossil fuel generation.

In the Clean Energy scenario, using base case fuel price assumptions (i.e., based on 2012-2021 trends), combined RE generation capacity rises to 110 GW in 2030 and 182 GW in 2035, exceeding the government's goal and providing 36% and 50% of total electricity generation, respectively. Offshore wind capacity increases rapidly in this scenario, due to continued declines in technology costs (Figure ES1).

The combination of existing nuclear capacity, most existing natural gas capacity, and new battery storage is sufficient to meet Korea's electricity demand reliably (i.e., in every hour of the year) on an 80% clean grid in 2035. In the Clean Energy scenario with base fuel prices, all coal-fired electricity generation is phased out by 2035 and no new fossil fuel plants are built. Under normal operating conditions, RE, nuclear, and natural gas provide 50%, 30%, and 20% of annual electricity generation, respectively. Further, the Clean Energy scenario's mix of electric generating resources is sufficient to reliably meet summer and winter electricity net loads while maintaining an 8% operating reserve margin. Additionally, up to 37 GW of existing coal generation could be retired without affecting reliability.

Figure ES1. Generation Energy Mix and Total Installed Capacity Between 2022 and 2035, Clean Energy Scenario with Base Fuel Price Case



Electricity Supply Costs from the 80% Clean Grid are Lower Than Today's Costs

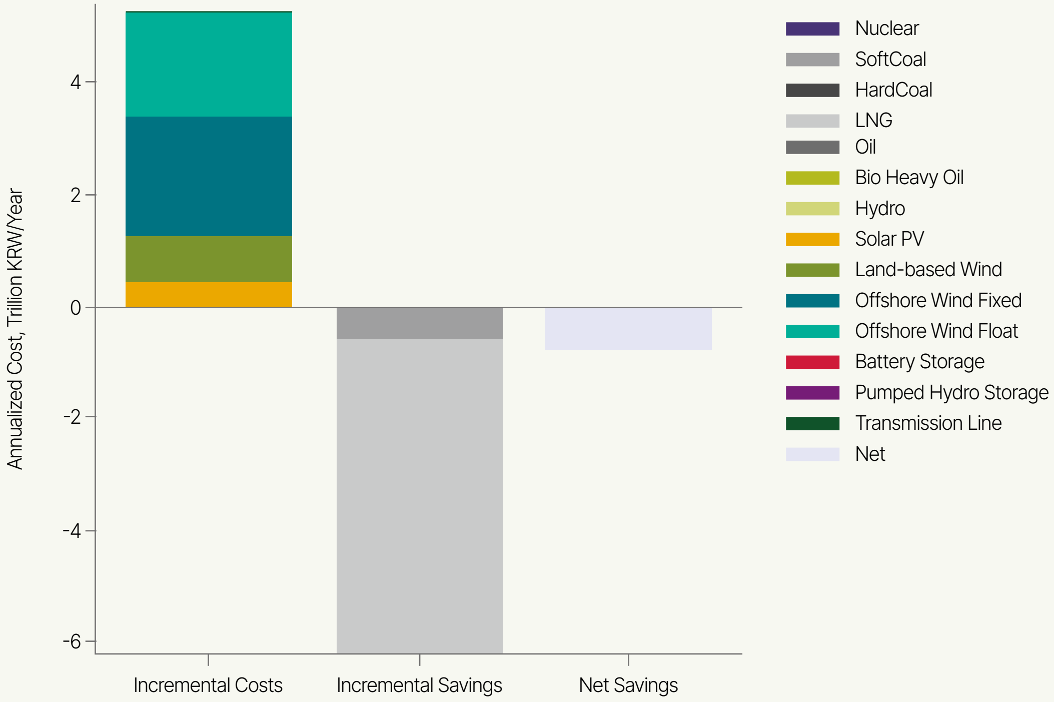
In both the Current Policy and Clean Energy scenarios, under base case assumptions for RE and storage costs, wind and PV generation are the lowest cost and most scalable RE resources. In the Current Policy scenario, combined wind and solar generation capacity is consistent with the government's goal of producing 21% (75 GW) from clean energy sources by 2030 and 35% (139 GW) by 2035. In the Clean Energy scenario, the combined wind and solar capacity rises to 36% of electricity generation (110 GW) in 2030 and 50% (182 GW) in 2035. Energy storage capacity increases rapidly in both scenarios, due to continued declines in battery costs (see Table ES1).

Table ES1. Key Differences in the Current Policy and Clean Energy Scenarios

Metric	Year	Current Policy Scenario	Clean Energy Scenario
Change in coal generation relative to 2022	2030	-98 GWh	-107 GWh
	2035	-173 GWh	-210 GWh
Coal generation capacity	2030	15 GW	15 GW
	2035	8 GW	0 GW
Clean energy (non-fossil) generation share	2030	55%	71%
	2035	65%	80%
Wind and solar generation capacity	2030	75 GW	110 GW
	2035	139 GW	182 GW
Energy storage capacity	2030	8.5 GW	8.5 GW
	2035	32.9 GW	42.3 GW

Electricity supply costs, inclusive of generation and transmission costs, are lower in the Clean Energy scenario (in which wind, solar, and battery storage displace a significant amount of generation from existing coal plants) than in the Current Policy scenario (in which generation from existing coal plants declines by only a small amount). In other words, the incremental cost of developing new solar and wind farms, battery storage, and transmission infrastructure in the Clean Energy scenario is lower than the fossil fuel, operation and maintenance (O&M), and fixed costs of running existing coal-fired plants (Figure ES2). This suggests that a **more rapid deployment of wind and solar generation** – up to an average of 14.5 GW per year between 2030 and 2035 in the Clean Energy scenario – **would *reduce* electricity supply costs**. Retaining natural gas-fired power plants helps balance seasonal and daily load variations against variable solar and wind generation, thereby reducing the need for long-duration energy storage and further renewable plant buildout.

Figure ES2. Annualized Incremental Costs, Incremental Savings, and Net Savings in the Clean Energy Scenario, Relative to the Current Policy Scenario



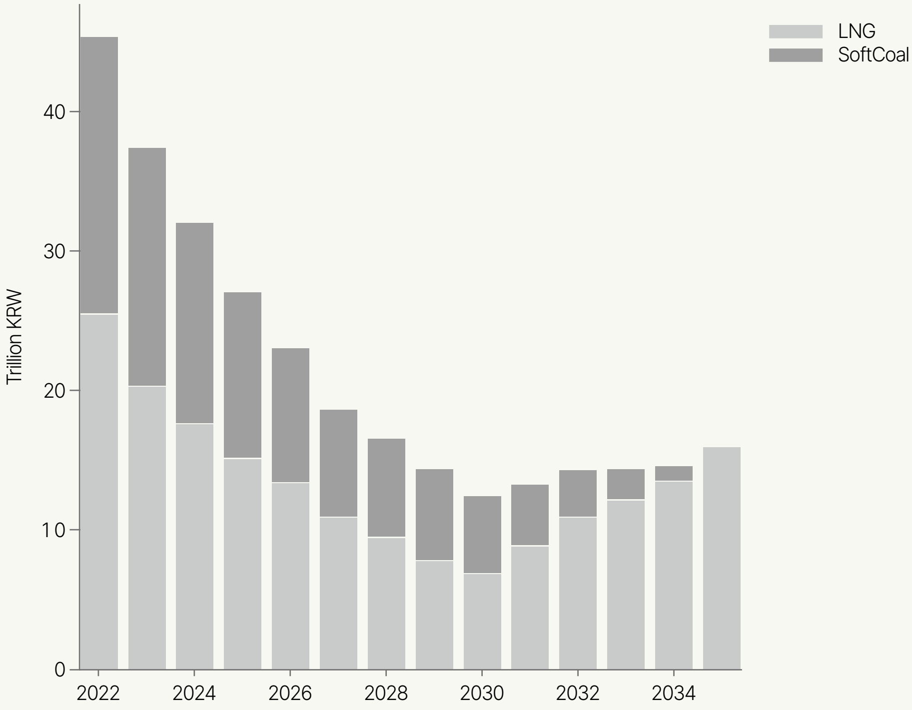
Scaling Up Renewables to Achieve an 80% Clean Grid Is Feasible

Under the Clean Energy scenario, the combined capacity of all RE sources rises from 26 GW in 2022 to 110 GW in 2030 and 182 GW in 2035 (Figure ES1). In particular, the accelerated growth of wind and solar capacity makes an 80% clean grid feasible. Solar power additions are dominant in the 2020s, while offshore wind becomes dominant in the 2030s due to its continued technology cost declines and high capacity factors.

An 80% Clean Grid Bolsters Korea's Energy Security by Significantly Reducing Fossil Fuel Imports

Under the 80% Clean Energy scenario, imported coal and natural gas costs would decrease by up to 62%, from 48.1 trillion KRW in 2022 to 18.5 trillion KRW in 2035. This reduction would be even greater under the high fuel cost sensitivity scenario, which maintains 2022 prices. Maximizing the utilization of domestic renewable resources significantly decreases Korea's heavy dependence on imported fossil fuels, in turn bolstering its energy security and insulating consumers and the economy from the risk of skyrocketing international fossil fuel prices.

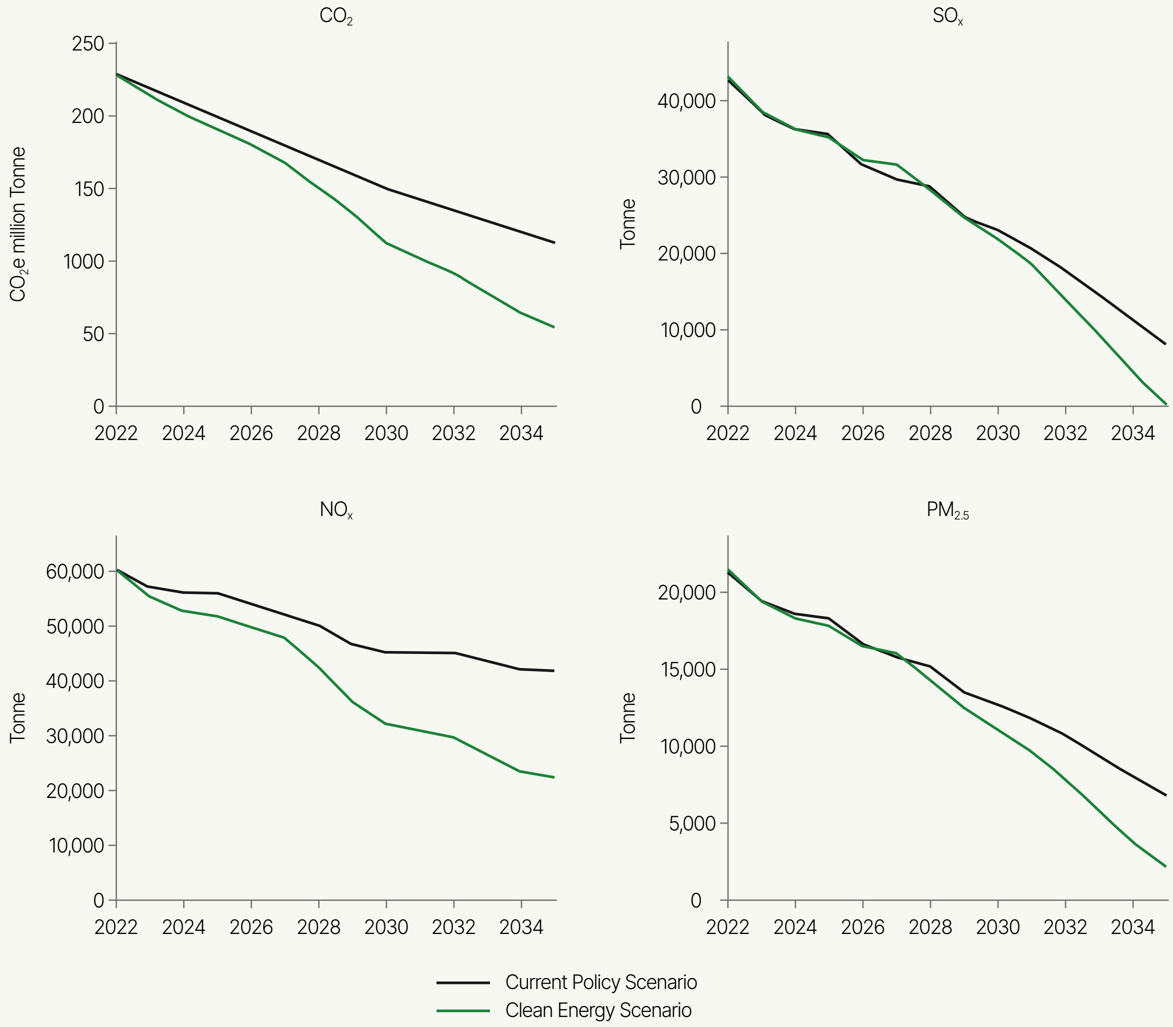
Figure ES3. Imported Fuel Costs for Power Generation in the Clean Energy Scenario



Achieving Clean Energy Goals Dramatically Reduces Emissions of CO_2 and Other Air Pollutants

Reaching an 80% clean electricity grid by 2035 would deliver deep cuts in carbon emissions, along with other environmental benefits. By 2035, the Clean Energy scenario reduces electricity sector carbon dioxide (CO_2) emissions by 76% below 2022 levels, and 52% below the Current Policy scenario. Similarly, emissions of nitrogen oxides (NO_X), sulfur oxides (SO_X), and fine dust ($PM_{2.5}$) fall by 46%, 100%, and 69%, respectively. Electrification of the transportation, industrial, and buildings sectors would reduce emissions even further.

Figure ES4. Electricity Sector Emissions of CO_2, SO_X, NO_X and $PM_{2.5}$ Through 2035



Capturing All Available Cost-Effective Clean Electricity Generation Requires Overcoming Policy, Market, and Land Use Barriers

Rapid deployment of wind, solar, and energy storage technologies will require changes in policies that regulate electricity generation, markets, and land use. The accompanying report, *Korean Power System Challenges and Opportunities: Priorities for Swift and Successful Clean Energy Deployment at Scale*, discusses these barriers and possible policy pathways in greater detail.

The share of clean energy generation in the Current Policy and Clean Energy scenarios begins to diverge in the 2022-2025 time period, suggesting that policy and regulatory changes to accelerate RE deployment should begin in the 11th Basic Plan period (2024-2038). In particular, while momentum may already support the accelerated deployment of wind and solar energy, significant barriers still impede energy storage deployment. Faster decarbonization of Korea's electricity system would, in turn, make electrification available to support CO_2 emission reductions in other sectors, smoothing the country's path to a carbon-neutral economy by 2050.

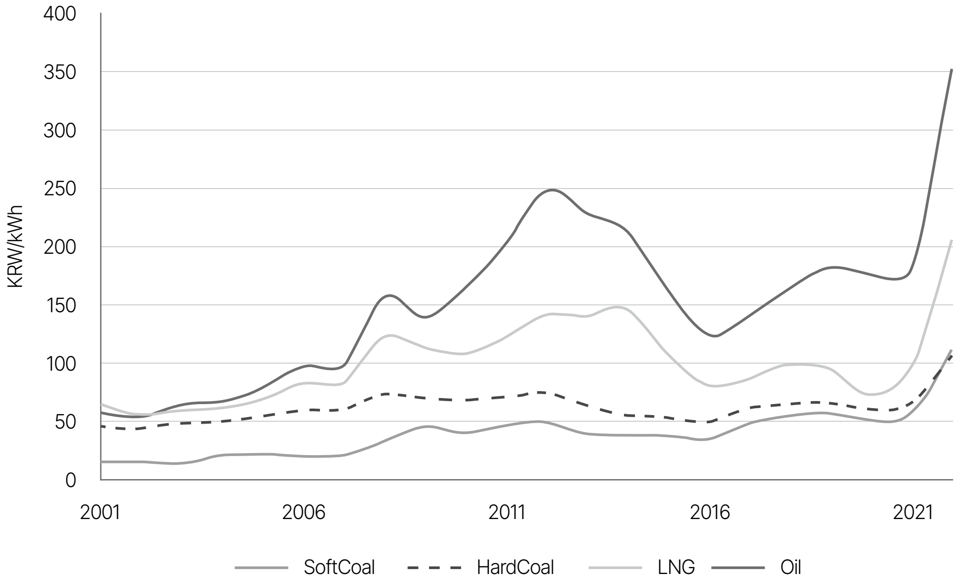
1.
INTRODUCTION

In October 2018, the United Nations Intergovernmental Panel on Climate Change (IPCC) reported that global carbon emissions must be halved by 2030 to limit warming to 1.5°C and avoid catastrophic climate impacts (IPCC 2018). In October 2020, Korea – the world's eleventh largest greenhouse gas (GHG) emitter – pledged to become climate neutral by 2050 (UNFCCC 2021). One year later, the Korean government adopted an enhanced nationally determined contribution (NDC) target for 2030 to reduce emissions 40% below 2018 levels.

While Korea's commitments can contribute to global climate goals, the Korean NDC target for 2030 – which relies on international carbon credits, as well as carbon capture, utilization and storage (CCUS) – is insufficient and incompatible with the 1.5°C target set forth by the Paris Agreement (GESI et al. 2022). In addition, while targets are important, a concrete implementation pathway for Korea, supported by sound policy instruments, has been lacking.

Long-term fuel price trends in Korea are highly uncertain, in that oil and gas prices rose to record levels in 2011, and again in 2022 – in the latter case, by 109% compared to average prices over the prior decade (Figure 1). In 2020, only 7% of Korea's primary energy was supplied by domestic resources (KEEI 2021). Liquified natural gas (LNG) and coal power plants still account for roughly 64% of the nation's electricity generation, exposing consumers and the overall economy to highly volatile international fuel prices.

Figure 1. Long-term Fuel Price Trends in Korea from 2001 to 2022



Source: EPSIS (2023)

Technological advancements and dramatic cost reductions in solar, wind, and battery storage create new opportunities to reduce emissions and costs related to electricity generation in many countries (see Shiraishi et al. 2023; Bistline et al. 2022; Abhyankar et al. 2022; Abhyankar et al. 2021; Phadke et al. 2020 for the U.S., China, and India). The electricity sector will play a pivotal role in meeting Korea's environmental goals, including both the 2050 carbon neutrality and 2030 NDC goals. Increases in non-fossil generation, combined with electrification in the transportation, industrial, and building sectors, can generate significant reductions in emissions.

Several studies have analyzed the power sector's transition to RE and decarbonization in Korea. Park et al. (2013) explored different scenarios for achieving this transition by 2050, concluding that a mix of RE sources is necessary to achieve significant reductions in GHG emissions. Song et al. (2018) analyzed various energy transition strategies using a power market simulation model, identifying phasing out either nuclear energy or coal (but not both) as viable options. Park et al. (2019) evaluated RE potential scenarios, suggesting a weather-driven hourly simulation scenario can meet emission targets by 2030 with reduced coal generation. Kim et al. (2022) analyzed technology pathways for achieving carbon neutrality by 2050, emphasizing rapid decarbonization of the power sector and the electrification of end-uses. These findings provide valuable insights into the challenges and opportunities for transitioning to clean energy and decarbonization in Korea. However, few or no studies have examined accelerated decarbonization pathways for Korea's power sector, particularly for a 2035 time horizon, by using capacity expansion and hourly dispatch models[5] and incorporating rapidly decreasing technology costs.

This report aims to inform discussion around three questions prior studies have not addressed. First, what effect will recent declines in wind, solar, and battery storage costs have on the pace and scale of renewable resource development in Korea? Second, what clean energy goals are technically and economically feasible, given inherent uncertainties around electricity demand growth, fossil fuel prices, and RE and energy storage costs? Third, how can a faster transition to clean energy deliver not only environmental and economic benefits, but also reduce security risks related to dependence on imported fossil fuels?

This report examines the technical feasibility, costs, and implications of increasing the share of electricity generated from clean energy in Korea to 80% by 2035. The analysis uses state-of-the-art modeling tools along with detailed load, wind, and solar profiles and wind, solar, and energy storage cost projections.

Section 2 of this report provides an overview of the methods used in the electricity and emissions analyses, while Section 3 describes two categories of results: (1) changes in generation and transmission, and (2) cost, investment, reliability, and emissions. Section 4 describes caveats for this analysis. Section 5 summarizes key conclusions from the study. Appendices provide more detailed information on the modeling approach, data inputs and sources, load shape development, and wind and solar profile development. The accompanying report, *Korean Power System Challenges and Opportunities: Priorities for Swift and Successful Clean Energy Deployment at Scale*, discusses these barriers and possible policy pathways in greater detail.

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[5] Capacity expansion models are used to determine the optimal mix of energy sources required to meet energy demand while minimizing costs and emissions. Hourly dispatch (or production cost optimization) models help to determine the most efficient and cost-effective way to dispatch electricity from different energy sources throughout the day.

2.

METHODS AND DATA SUMMARY

This study draws on intensive scenario building, data development, and power system modeling using detailed, best-available data inputs and state-of-the-art modeling tools. Analyses found in this report use capacity expansion and hourly dispatch models developed in the PLEXOS platform to forecast the years 2025, 2030, and 2035.

The models are based on a detailed representation of Korea's electricity system, including hourly regional loads, interregional transmission constraints, region-specific wind and solar profiles, and recent RE and electricity storage cost projections. The electricity demand forecast used in the analysis is based on Korean government projections and reflects necessary changes in the electricity system to meet 2050 climate goals.

This section provides a brief overview of scenarios, key inputs and assumptions, modeling tools and approach, and sensitivity analyses. The Appendices include detailed descriptions of methods used for modeling and the development of hourly load, wind, and solar profiles.

2.1 Policy Scenarios

The analysis examines two core scenarios. The Current Policy scenario reflects current policies (i.e., 2030 NDC targets, 2050 carbon neutrality goal, and the 10th Basic Plan) and technology cost trends in Korea, leading to a clean energy generation share of 65% in 2035.[6] In the Clean Energy scenario, where 80% of electricity is generated from clean sources in 2035, we examine whether this additional clean energy deployment is achievable, cost effective, and would maintain a reliable electricity grid. Sensitivity analyses explore variations in the Clean Energy scenario.

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[6] This is a little greater than 59% clean electricity generation by 2036 in the 10th Basic Plan.

The Current Policy and Clean Energy scenarios differ mainly in their assumptions about coal generation capacity additions, RE generation capacity additions, and non-fossil energy generation share (Table 1).

First, the Current Policy scenario forces a net 5.4 GW of coal generation capacity additions into the model, based on plants currently under construction and some retirement of existing generation; it also assumes the extended operation of 10 nuclear reactors totaling 11.25 GW of emissions-free generating capacity, based on a plan under consideration. The Clean Energy scenario does not force this net 5.4 GW of coal generation into the model, but rather forces the phase-out of coal-fired power generation by 2035.

Second, the Current Policy scenario assumes the amount of new wind and solar generation that can be added in any given model year is limited to the amount required to meet current policy targets and their implied trajectories in 2035. In the Clean Energy scenario, these limits are relaxed, and new wind and solar generation capacity additions are determined based on their economic competitiveness within their annual installation capacity limits.

Lastly, in the Current Policy scenario, the model builds non-fossil generation to provide 55% of generation in 2030 and 65% in 2035. In contrast, the Clean Energy scenario has no constraints on non-fossil generation.

Table 1. Policy Scenarios Benchmarked Against National Goals

	NATIONAL GOALS		2035 SCENARIOS DEVELOPED IN THIS REPORT	
			CURRENT POLICY SCENARIO	CLEAN ENERGY[a] SCENARIO
Reference policies/ plans	• New 2030 NDC Target • 2050 Carbon Neutrality Goal	10th Basic Plan for Long-term Electricity Supply and Demand (10th Basic Plan)	• National goals • Nuclear extension	
Coal generation capacity additions	5.4 GW	4.2 GW	5.4 GW	• No new coal generation is forced into the model. • Coal generation is phased out by 2035.
RE generation capacity additions	RE ~30% in generation share by 2030 (70 GW solar and 22.5 GW wind capacity)	RE ~25% in generation share by 2036 (65.7 GW solar and 34 GW wind capacity)	Limited to RE deployment (21% in 2030 and 35% in 2035) and emission reduction targets by 2035	Determined to meet emission reduction targets by 2035 and cost competitiveness
Clean (non-fossil) energy generation share	57.7% by 2030 • RE 30.2% • Nuclear 23.9% • NH_3 3.6%	59.3% by 2036 • RE 24.7% • Nuclear 34.6%	55% in 2030 65% in 2035	Determined by model's least-cost optimization
Nuclear extension	Not included	• 10 nuclear reactors (11.25 GW) operation extended • 2 new nuclear reactors (2.8 GW) added in 2033 and 2034		
H_2 or NH_3	NH_3 3.6% (2030)	7.1%[b]	H_2 included (determined by model's least-cost optimization)	
Electricity generation projected	612.4 TWh in 2030, 1257 TWh in 2050	667.3 TWh in 2036	612.4 TWh in 2030 776.6 TWh in 2035	

[a] Clean energy in this report refers primarily to RE (solar, wind, hydro and marine energy) and nuclear. Biofuel, fuel cell, integrated gasification combined cycle (IGCC) are not included because they are not defined as clean energy.

[b] H_2 and NH_3 in the 10th Basic Plan are not assured to be green or blue.

[c] See Figure 2

Sources: MOTIE (2023), CNC (2021), and UNFCCC (2021)

2.2 Modeling Tools and Approach

The electricity system analysis was conducted using PLEXOS, a modeling platform widely used for industry-standard power systems analysis. A two-stage modeling approach was used to develop least-cost portfolios for each scenario, and then examine operating costs, emissions, and reliability based on direct current (DC) power flows.

Models included generation resources, generation constraints, unit commitments, and interregional transmission constraints for 11 nodes connected by 17 interregional transmission corridors (Figure 2). This analysis assumed the electricity system was balanced and reserves were managed at a regional scale, enabling resources to be shared efficiently among provinces.

Figure 2. Transmission Network Included in the Modeling

Orange dash lines represent virtually established West Coast transmission lines in the model (see Table 3), while black lines represent existing transmission lines.

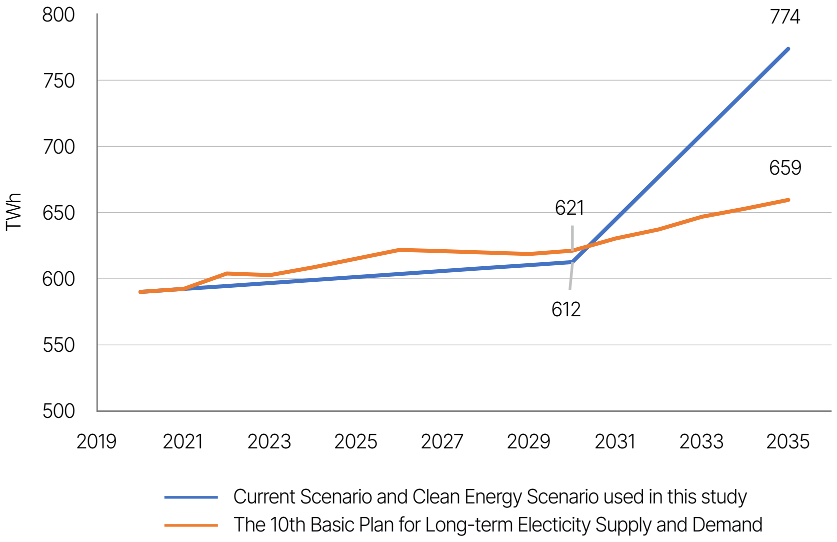
Source: Authors’ work.

2.3. Key Modeling Inputs

Electricity Demand

Korea's electricity demand is expected to grow by 2035 and will depend on the structure and pace of economic growth, as well as the pace of electrification in the transportation, industry, and buildings sectors. This study is based on government projections used with the 2030 NDC and 2050 Carbon Neutrality goals.

Figure 3. Korea's Projected Annual Electricity Generation



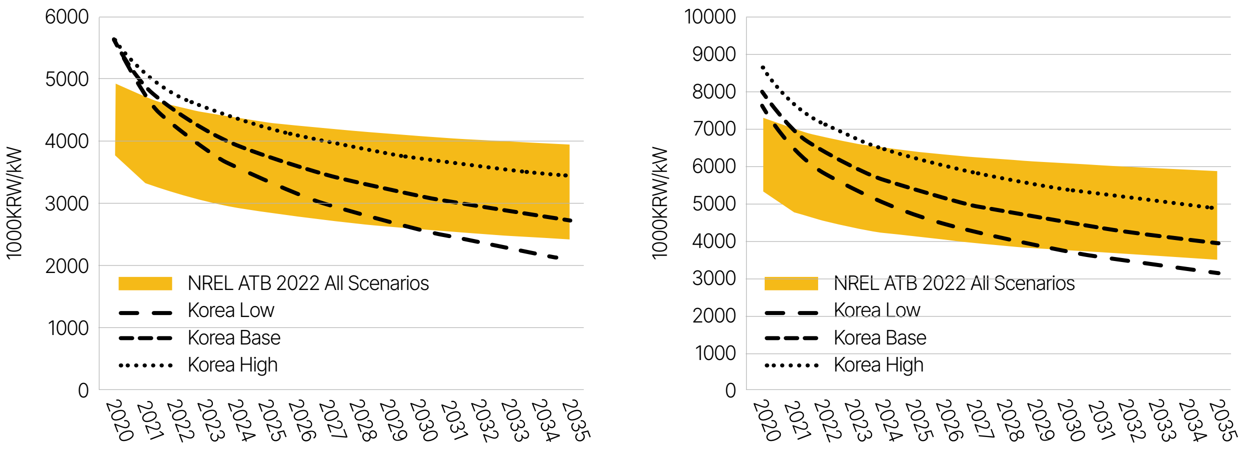
Source: MOTIE (2023) and UNFCCC (2021)

Technology and Fuel Costs

Extensive resource cost inputs included those for wind, solar, and battery storage, as well as coal and gas fuel. Annual technology base (ATB) scenarios from the National Renewable Energy Laboratory (NREL) provided projections of installed and fixed operations and maintenance (O&M) costs for land-based wind, offshore wind, solar PV, and storage in the U.S. Phadke et al. (2020) emphasized that rapid, cost-effective decarbonization becomes more achievable because of the significant accompanying decrease in costs and cost projections for wind and solar energy. They pointed out that NREL ATB's projections in terms of levelized cost of electricity (LCOE) were revised downwards almost every year between 2015 and 2019.

Because technological advancements occur alongside uncertainty, the technology costs (Low, Base, and High) for Korea's RE and storage in this study are based on Lee & Kim (2020) for baseline costs in 2020 that are later assumed to converge on NREL ATB's Advanced scenario in 2030 (Low), Moderate scenario in 2035 (Base), and Conservative scenario in 2035 (High). The model also considers 4-hour, 8-hour, and 12-hour battery storage durations, which all have cost declines similar to those for 4-hour batteries (Figure 4).

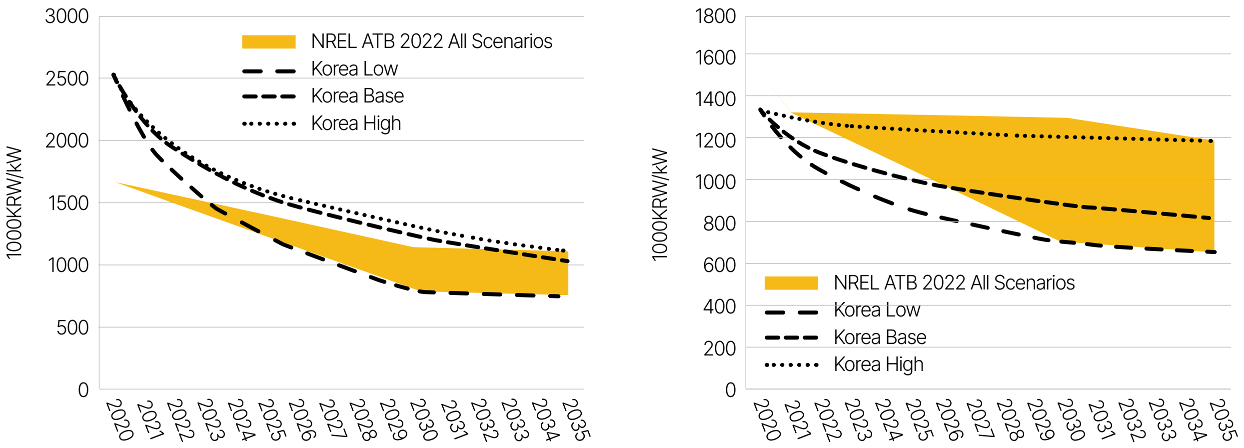
Figure 4. Technology Cost Inputs for Offshore Wind, Land-based Wind, Solar PV, and Battery Storage (4-hour)



OFFSHORE WIND COSTS (FIXED BOTTOM)

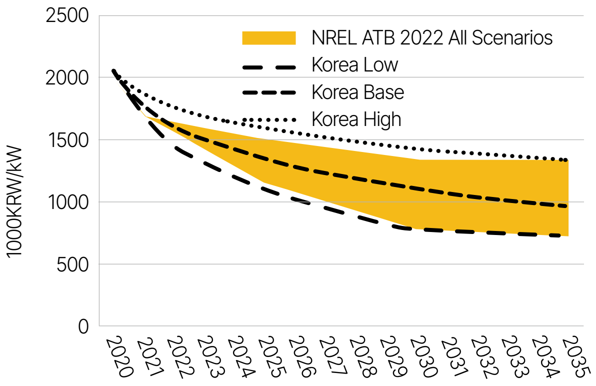
OFFSHORE WIND COSTS (FLOATING)

Figure 4. Technology Cost Inputs for Offshore Wind, Land-based Wind, Solar PV, and Battery Storage (4-hour)



LAND-BASED WIND COSTS

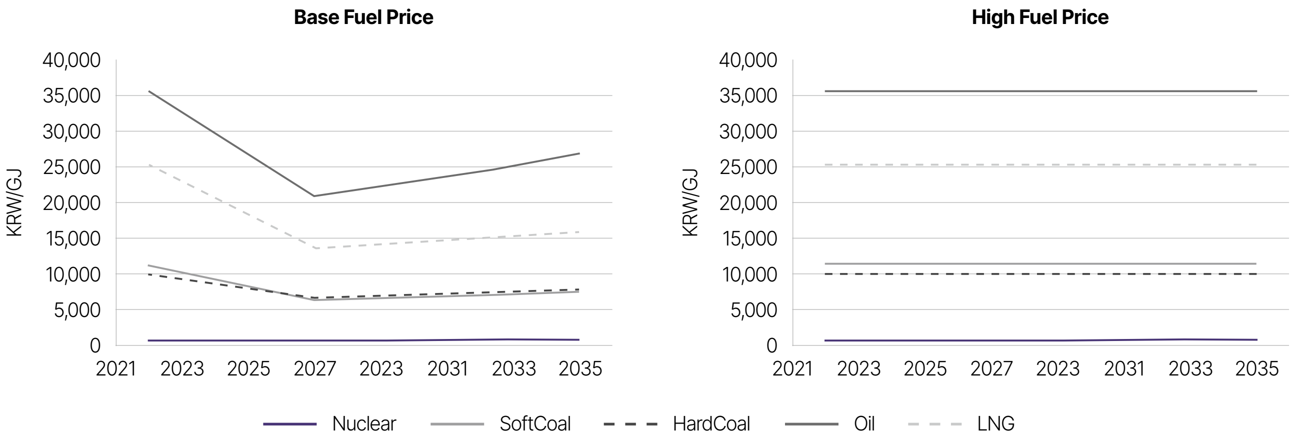
SOLAR PV COSTS



UTILITY-SCALE BATTERY (4-HR) COSTS

Longer-term fuel price trends in Korea are highly uncertain. Oil and gas prices rose to record levels in both 2011 and 2022. Coal supply and demand tend to keep prices close to marginal production and transport costs. This study's High Fuel scenario assumes Korea's average 2022 fuel prices remain constant until 2035, whereas the Base Fuel scenario assumes prices decline to 2001-2021 averages (EPSIS 2023) until 2027 before increasing to reflect the U.S. Annual Energy Outlook (AEO) Reference Scenario forecast (EIA 2022). The Current Policy and Clean Energy scenarios use the same technology cost and fuel cost assumptions (Figure 5).

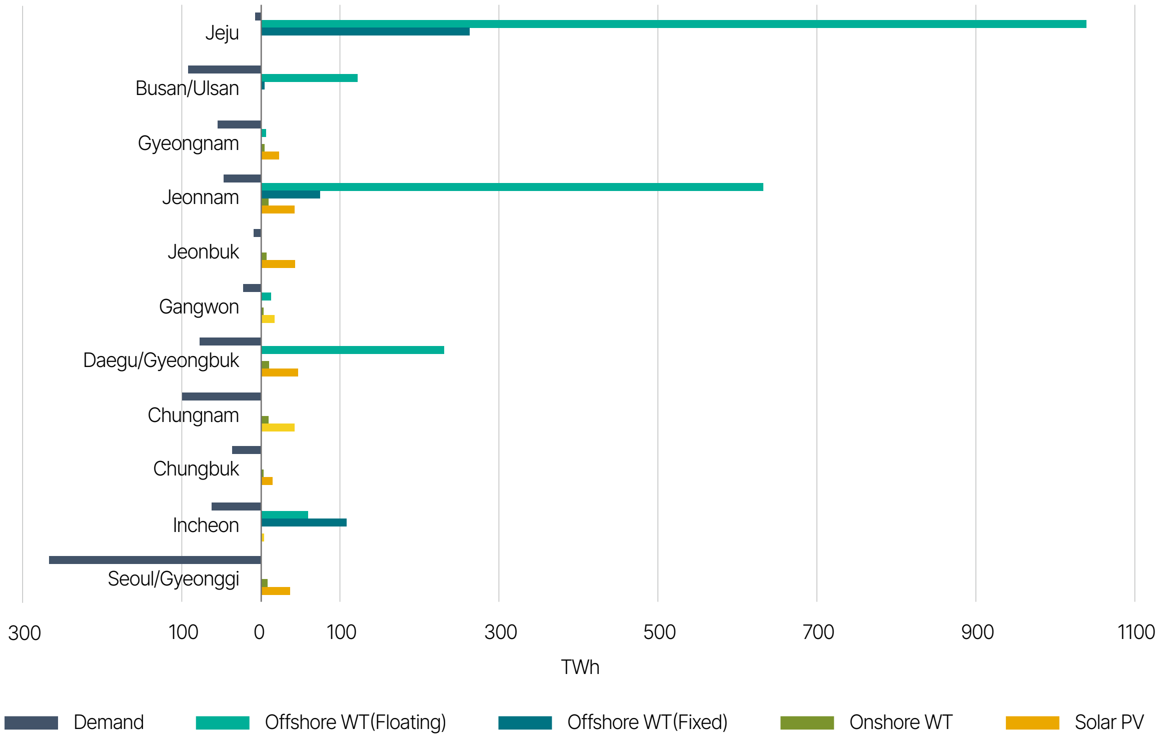
Figure 5. Fuel Price Inputs for Oil and Gas



Solar and Wind Profiles

For this study, we estimated wind and solar resource potential and developed detailed solar and wind profiles for each province in Korea. The methodology can be divided into two parts, the first of which involves estimating the resource potential (i.e., the maximum solar and wind capacity that can be installed in a province). We use average annual capacity factors from the Global Wind and Solar Atlas and apply multiple exclusion criteria (e.g., elevation, slope, landcover, natural parks, defense areas, fishery zones and ocean depth) to estimate the potential for both solar and wind. The second part of the methodology involves developing detailed hourly generation profiles. For this, we use meteorological data from reanalysis datasets and simulate site-level wind and solar generation using NREL's System Advisor Model (SAM) (NREL 2017). Typical wind and solar farms are designed in SAM, and hourly generation is estimated by passing meteorological data through it. We then use an aggregation algorithm to combine hourly generation from multiple sites in a given province to create a representative provincial wind and solar resource profile. For offshore wind, we develop multiple clusters for fixed and floating wind projects using a spatially constrained multivariate clustering algorithm, and then develop profiles for each cluster. Our complete methodology and data sources are discussed in detail in Appendix C.

Figure 6. RE Potential and 2035 Projected Electricity Demand by Region



Nuclear Generation

Because nuclear generating capacity is often built for reasons other than economics, this study assumed a nuclear generation capacity that is based on policy targets, rather than cost. It was assumed that nuclear generation capacity would increase as a result of a 20-year lifetime extension of 10 nuclear reactors to meet the policy target of 32.8% (11.25 GW) in the 2030 generation mix. It was also assumed that Shin-Hanul Units 3 and 4, having 1.4 GW capacity each, would be added in 2033 and 2034, respectively.

Modeling Scenarios

Table 2 shows the two core modeling scenarios considered in this study, including policy, technology cost, and fuel price assumptions, while Table 3 summarizes other assumptions used in this study.

Table 2. Combined Modeling Scenario of Policy, Technology Costs and Fuel Prices

	Policy	RE & Storage Costs	Fuel Prices
Two core modeling scenarios	Current Policy (reflecting government plans: 2030 NDC target, 2050 Carbon Neutrality Goal, and 10th Basic Plan)	Base case	Base case
	Clean Energy		

Table 3. Other Assumptions

Parameter	Assumptions
Coal retirements	Existing coal-fired plants retire at the end of their 30-year lifetimes. In Clean Energy Scenario, decreasing the amount of coal generation each year, until coal generation is completely phased out in 2035.
Gas retirements	Existing gas-fired plants retire at the end of their 30-year lifetimes.
Nuclear extension	Existing nuclear plants extend their lifetimes by renewing their generation licenses by 20 years at the end of their 40- or 60-year lifetimes.
Transmission expansion	Scenarios explored the outcomes of increasing transmission line capacity.
Solar PV	Solar PV facilities retire upon reaching their 25-year lifetimes and realize an average capacity factor (CF) of 17%.
Wind turbines	Wind turbines retire upon reaching their 25-year lifetimes and realize average CFs of 24% (land-based) and 36% (offshore).
Maximum annual capacity expansion	Annual deployment of solar PV, land-based wind, and offshore wind is limited to 6 GW, 2 GW, and 6.5 GW, respectively, based on expert consultation.
Transmission expansion	Starting in 2026, new transmission lines with a capacity of 2.5 GW between regions are allowed. Additionally, transmission lines with a capacity of 7 GW are established that connect the Seoul metropolitan area to the Jeonbuk, Jeonnam, and Jeju regions (see orange lines, Figure 2).

2.4. Sensitivity Analysis

The analysis considered four main sensitivities: low and high RE and storage costs; high fuel prices; and reliability (Table 4).

Table 4. Sensitivities to Low/High Technology Costs, High Fuel Prices, and Reliability Tests

Parameter	Assumptions
RE and storage costs	Low (Advanced) and High (Conservative) cases
Fuel price	High fuel prices (at 2022 levels), resulting in 1 GW more RE deployment per year (with solar PV rising from 6 to 6.5 GW and offshore wind rising from 6.5 to 7 GW)
Reliability	Deterministic wind and solar generation and load profiles were subjected to prolonged periods of low wind and solar generation and an unanticipated demand shock of 10% above forecast

Complete methodology and data sources are discussed in detail in Appendix B.

3.
KEY FINDINGS

The study's key findings are presented in two sections. Section 3.1 describes findings about generation mix, generation capacity mix, generation capacity additions, transmission capacity, and coal plant operations. Section 3.2 outlines findings about electricity supply costs, total investment, emission reductions, and reliability. Additional details can be found in the Appendices.

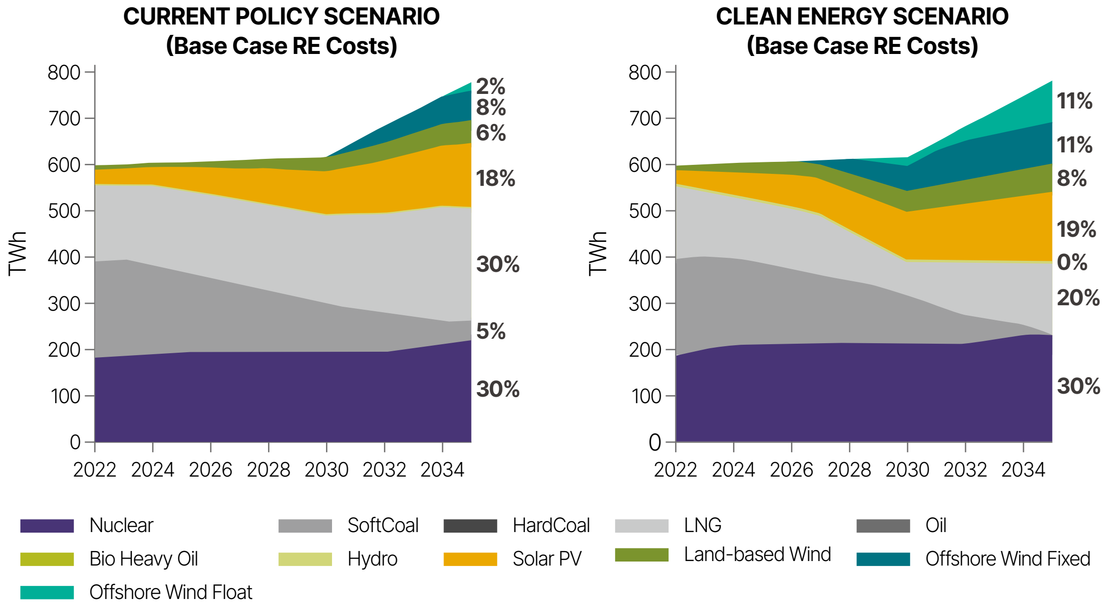
3.1 Generation, Transmission, and Storage

An 80% Clean Grid Is Reliable Without Coal Plants or New Natural Gas Plants – Even with Considerable Electricity Demand Growth

Even accounting for projected electricity demand growth through 2035, an 80% clean grid is reliable, meaning that it provides adequate energy in every hour of the year to meet demand. Wind and solar provide about half of daily generation, while nuclear provides an additional 30%. Under the Clean Energy scenario, existing hydropower and nuclear capacity are retained (except for planned retirements), all existing coal plants are retired by 2035, and no new fossil fuel plants are built. During periods of very high demand or very low renewable generation, existing natural gas, and nuclear plants combine cost-effectively with battery storage to compensate for mismatches between demand and wind and solar generation. Overall, natural gas plants would provide about 20% of total annual electricity generation, compared to about 32% today.

In the Current Policy scenario, clean energy generation increases from 35% of total generation in 2022 to 65% in 2035, and accounts for all new generating capacity. In the Clean Energy scenario, clean energy generation reaches 80% in 2035. The incremental increase in clean energy in the Clean Energy scenario is realized by expanding land-based wind, offshore wind, and solar PV (Figure 7).

Figure 7. Korea's Electricity Generation Mix Through 2035

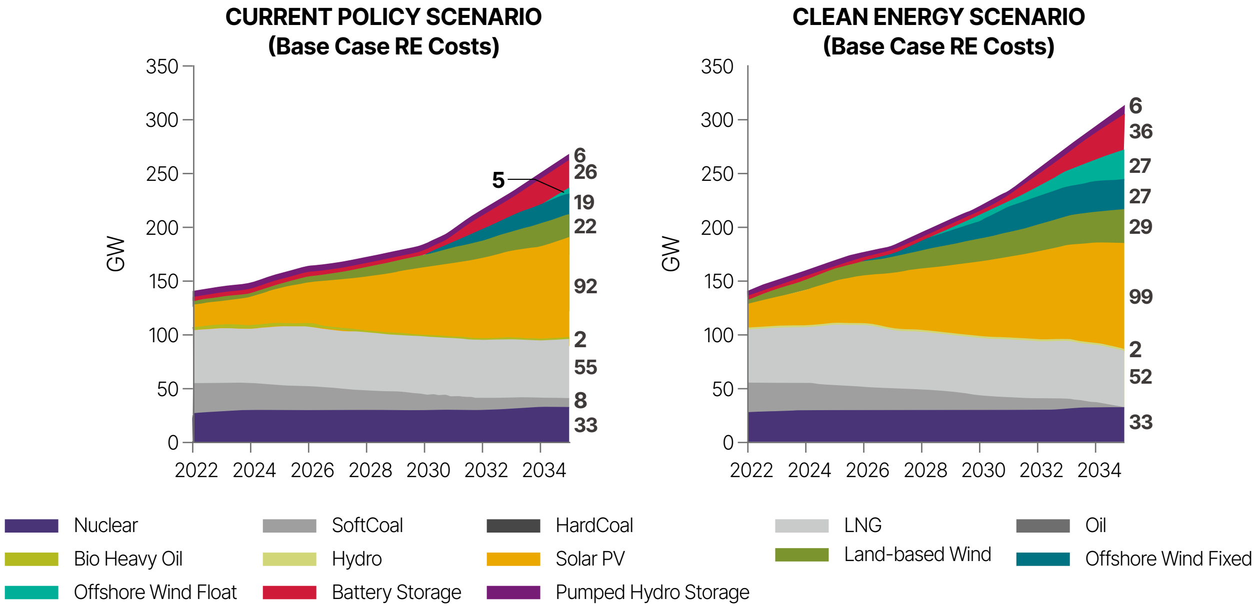


Electricity Demand Can Be Met Without Additional Coal-Fired Generation

In the Current Policy scenario, all new generation capacity additions are clean energy resources, aside from 5.4 GW provided by coal-fired generators under construction and 2.5 GW from LNG generators installed in 2035 (Figure 8). Wind and solar generation capacity reaches 75 GW in 2030 in the Current Policy scenario, in line with the government's 67.5 GW target for 2030, and then increases to 139 GW in 2035. Declining costs lead to rapid increases in energy storage deployment in the Current Policy scenario, with a total of 8.5 GW by 2025 and 32.9 GW by 2035. In the Clean Energy scenario, wind and solar generation and battery storage capacity increase more rapidly than in the Current Policy scenario (Figure 8). Divergence of the two scenarios begins in the 2022-2025 timeframe: renewable capacity reaches 50 GW by 2025 in the Clean Energy scenario, compared to just 38 GW in the Current Policy scenario. Wind and solar capacity grows to 110 GW by 2030 and 182 GW by 2035 in the Clean Energy scenario, 37% higher than required by current policy targets. By 2035, energy storage grows to 42.3 GW in the Clean Energy scenario.

Coal-fired power plant operations change significantly in both the Current Policy and Clean Energy scenarios, with steep declines in annual operating hours and increases in the variability of those hours. In the Current Policy scenario, average annual operating hours for coal plants fall from 7,800 hours per year (80% capacity factor) in 2022 to 6,250 hours per year (59% capacity factor) in 2035. In the Clean Energy scenario, these figures fall to zero.

Figure 8. Korea's Total Installed Capacity Through 2035

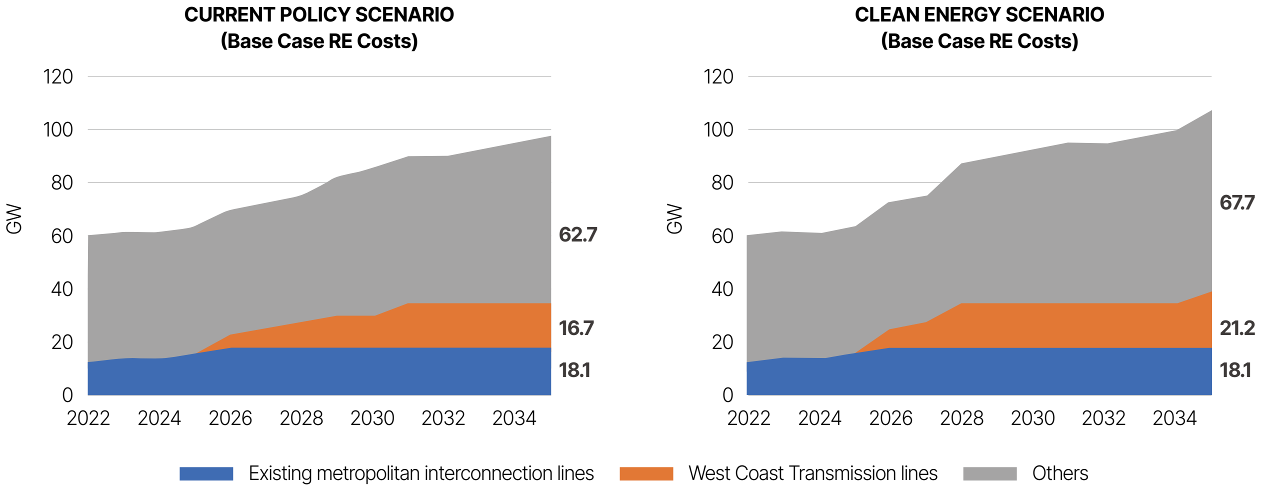


Sufficient Buildout of Clean Energy Transmission Capacity Can Be Accomplished with Nominal Incremental Investments

In both the Current Policy and Clean Energy scenarios, the model does not build any new interregional transmission capacity from 2022 to 2025, suggesting that all cost-effective capacity was already built by 2022. In the Clean Energy scenario, interregional transmission capacity starts at 60 GW in 2022 and increases to 92.5 GW in 2030, and 107 GW in 2035. This is 9.5 GW (5%) higher than the 97.5 GW transmission capacity in the Current Policy scenario for 2035. Compared to 2022, interregional transmission capacity increases by 25 GW and the West Coast transmission line increases by 21 GW in the Clean Energy scenario (Figure 9). Three main factors explain these outcomes:

- Given steep reductions in installed costs for solar PV and land-based wind, the model can cost-effectively build these resources closer to loads, instead of importing from regions with higher resource quality via long-distance transmission lines.
- Low-cost, grid-scale storage eliminates a large portion of new transmission investments needed for grid balancing.
- Electricity demand growth between 2022 and 2035 requires a large baseline transmission investment increase in the Current Policy scenario; by contrast, the Clean Energy scenario only requires modest incremental increases in transmission investment.

Figure 9. Transmission Capacity Expansion by 2035 in the Current Policy and Clean Energy Scenarios

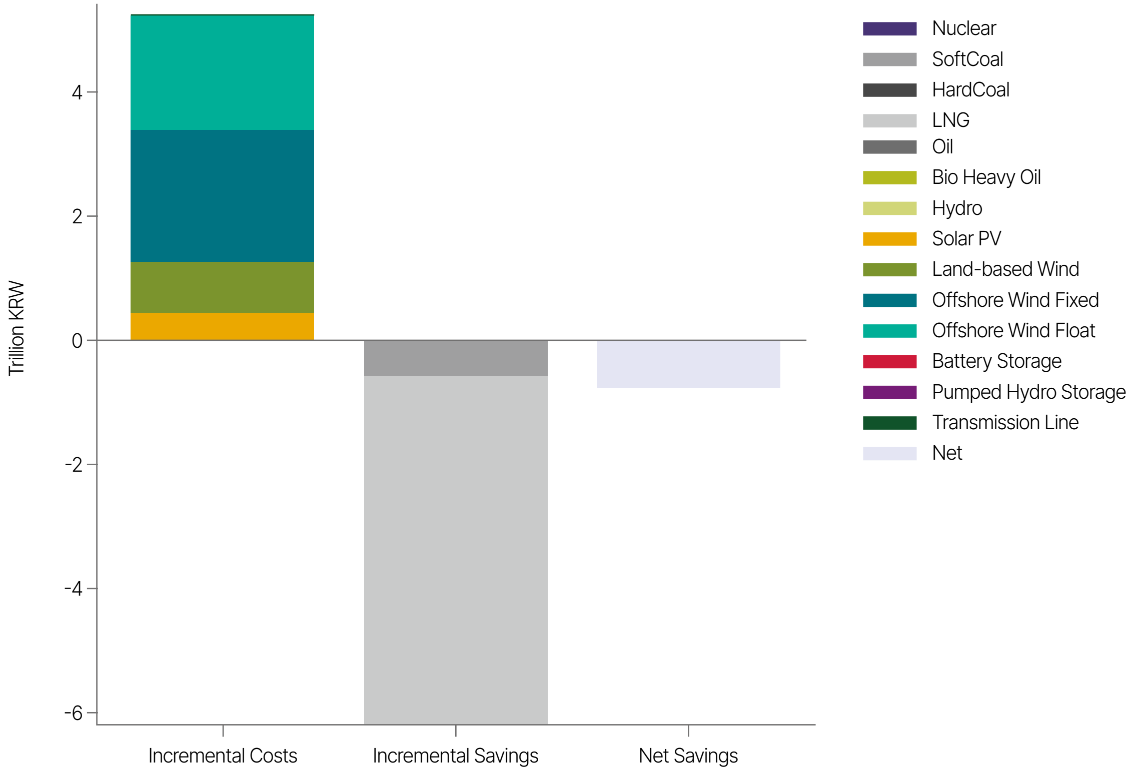


3.2 Cost, Reliability and Environmental Impacts

Clean Energy Deployment Can Lower Electricity Supply Costs

Electricity supply costs[7] in 2035 are 2% lower in the Clean Energy scenario than in the Current Policy scenario. This is because the incremental annualized costs for building more wind, solar, batteries, and transmission in the Clean Energy scenario (5.4 trillion KRW per year) are less than the savings from coal and natural gas fuels and operation (6.7 trillion KRW per year) and avoided new investments in coal generation (0.5 trillion KRW per year) (Figure 10). The Clean Energy scenario's lower electricity supply costs suggest that the Current Policy scenario's limits on annual wind and solar capacity additions are below cost-effective levels.

Figure 10. Annualized Incremental Costs, Incremental Savings, and Net Savings in the Clean Energy Scenario, Relative to the Current Policy Scenario



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[7] Electricity supply costs used in this report are defined as "wholesale costs" in other reports such as Abhyankar et al. 2022 and Phadke et al. 2020. These costs include installed capacity, fixed O&M, fuel costs for generation, storage, and installed capacity costs for interregional transmission.

In 2025, the total cumulative investment in the Clean Energy scenario is somewhat higher (by 2.3 trillion KRW) than in the Current Policy scenario, but by 2035 the difference in cumulative investment between the two scenarios grows to nearly 55.5 trillion KRW (86%) (Figure 11). As discussed above, this large increase in investment is essentially financed using coal and LNG fuel cost savings.

Figure 11. Cumulative New Capital Investment for Generation and Transmission

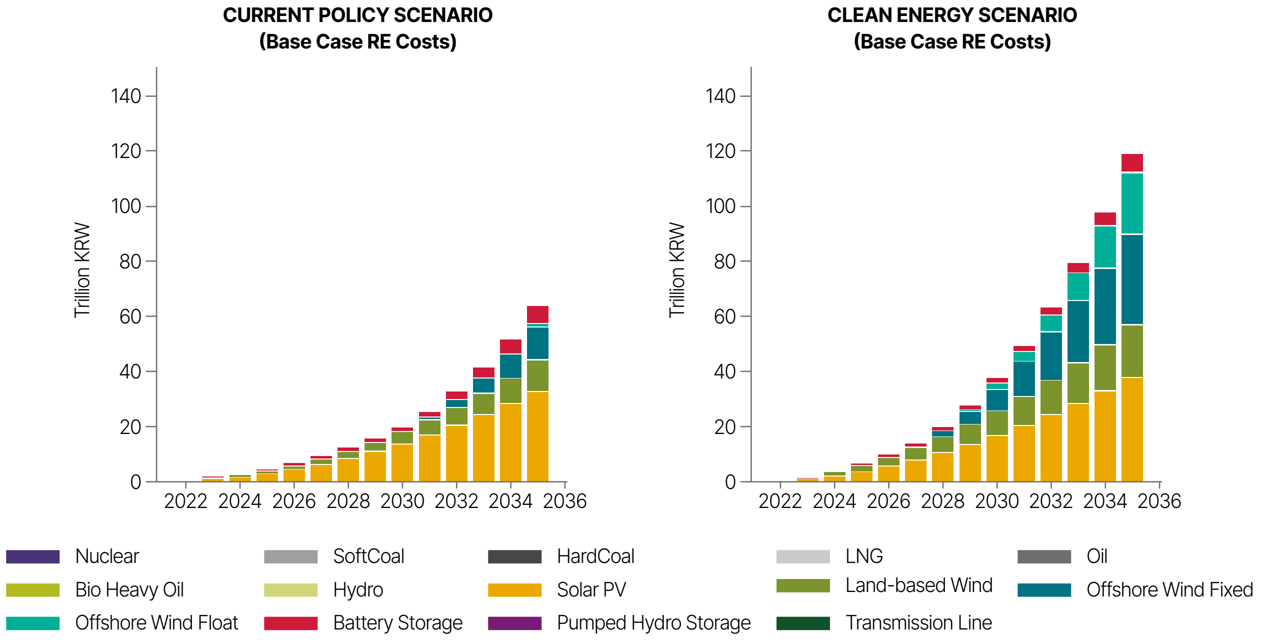
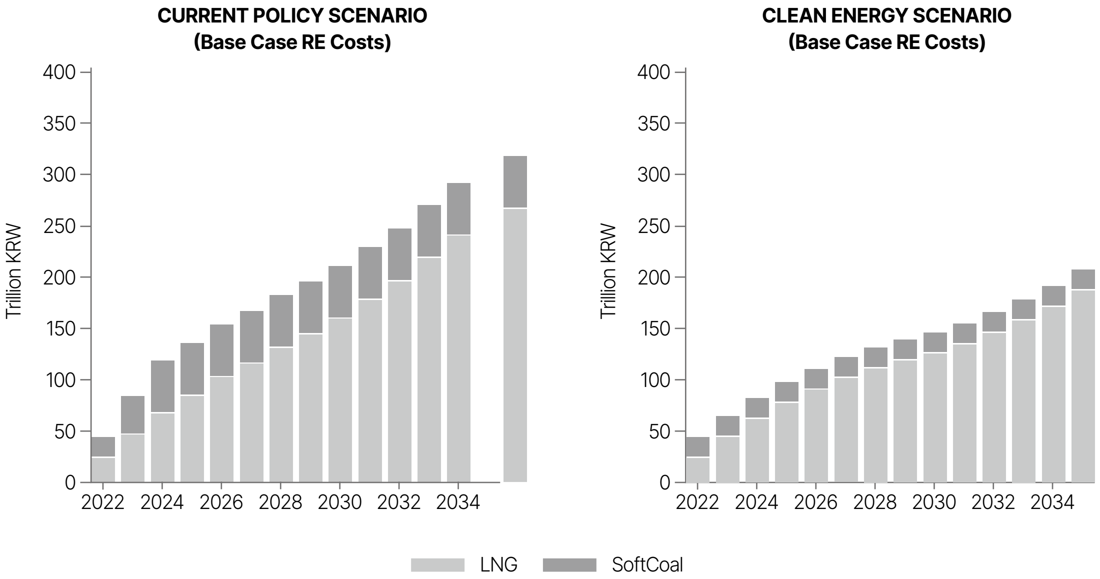


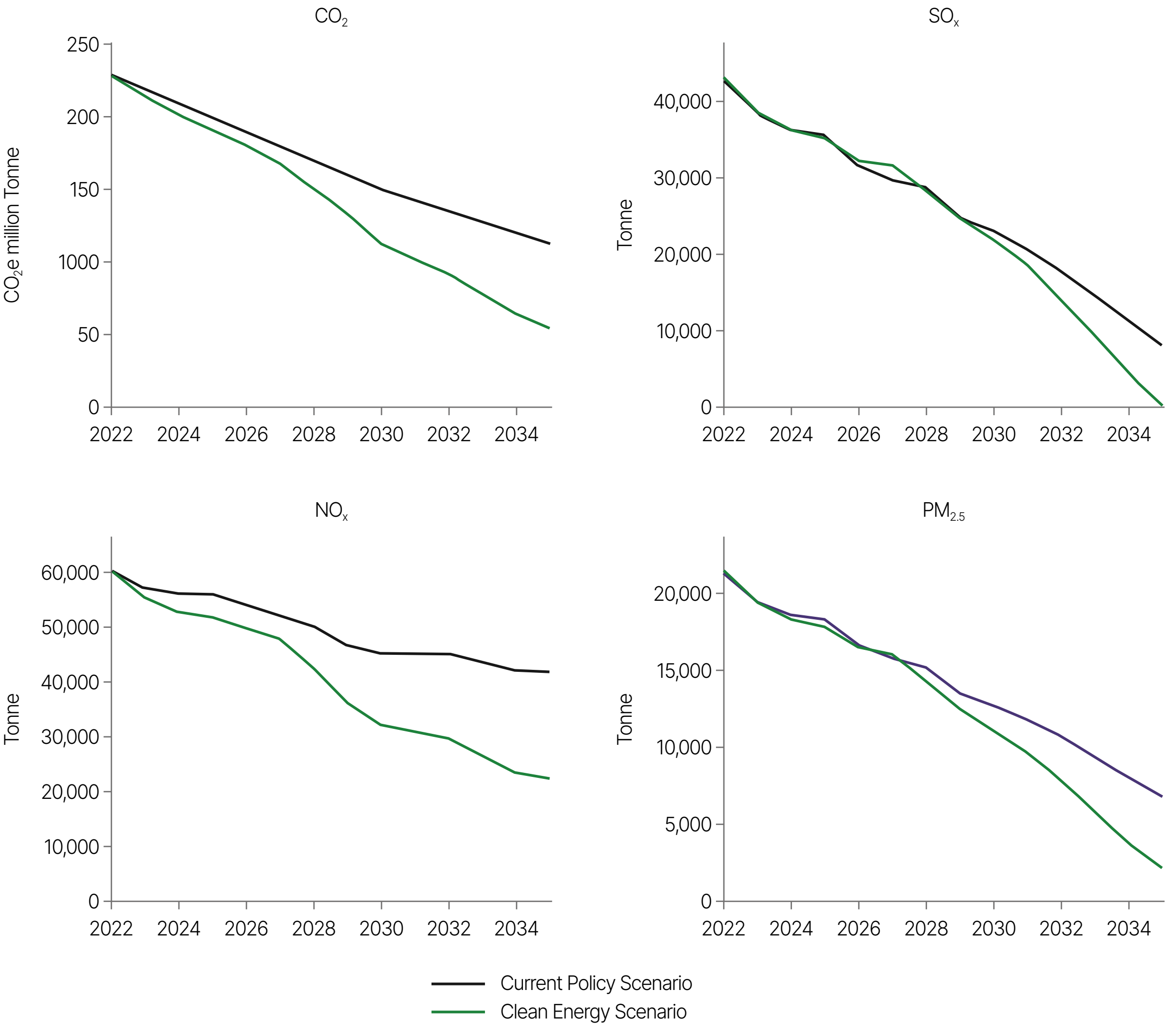
Figure 12. Cumulative Imported Fuel Costs for Power Generation



Clean Energy Cuts CO_2 Emissions By 76%, Providing Significant Environmental and Health Benefits

In the Current Policy scenario, emissions of CO_2, sulfur dioxide (SO_X), nitrogen oxide (NO_X) and fine dust ($PM_{2.5}$) fall by 51%, 81%, 31% and 68% from 2022 levels by 2035. In the Clean Energy scenario, between 2022 and 2035, CO_2 emissions decrease by 76%, to 54 $MtCO_2$ (Figure 11). Additionally, SO_X emissions decrease by 100% (8,000 metric tons), NO_X emissions are reduced by 46% (19,000 metric tons), and fine dust ($PM_{2.5}$) emissions fall by 69% (5,000 metric tons).

Figure 13. Electricity Sector Emissions of CO_2, SO_X, NO_X and $PM_{2.5}$ Through 2035

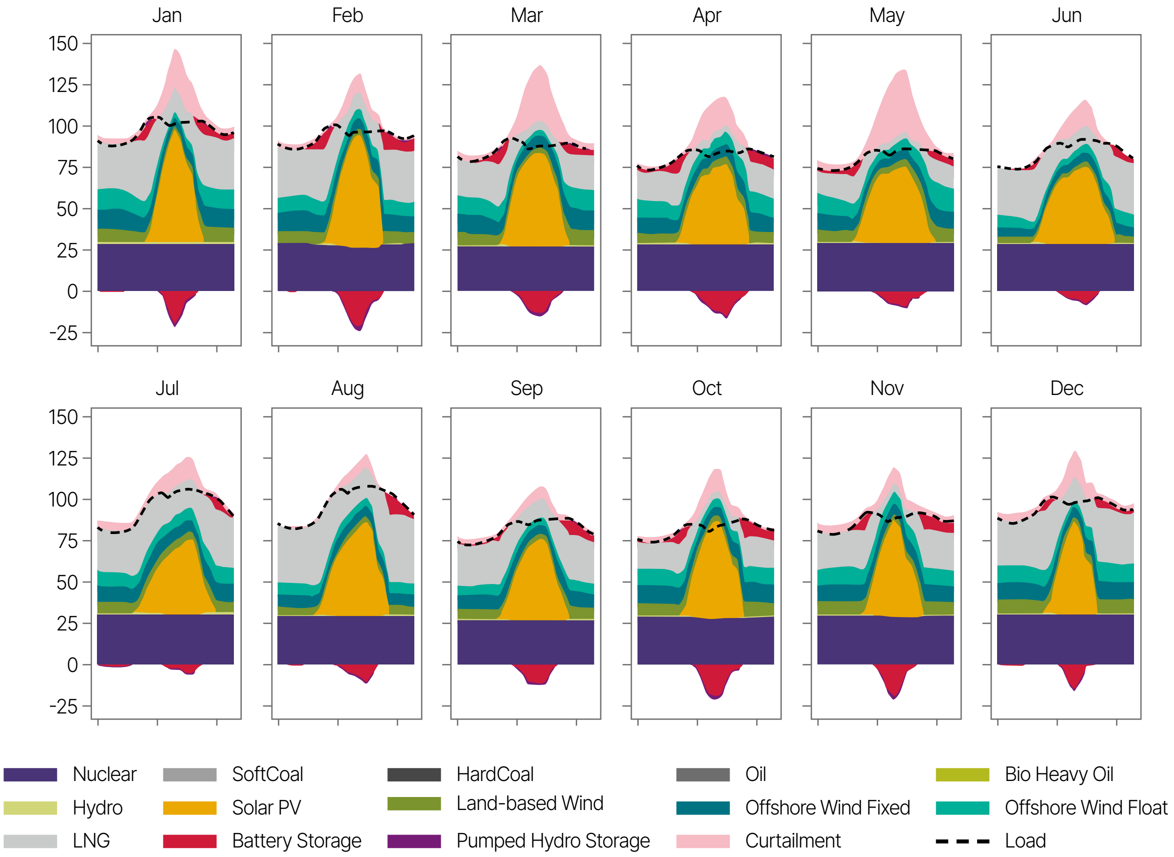


3.3 Sensitivity Analysis

Clean Energy Systems Can Reliably Meet Electricity Demands, Even with Coal-Fired Plant Retirements

Retirement of coal-fired plants after their 30-year lifetimes reduces Korea's coal capacity by about 15 GW, to 7 GW in 2035. Even so, the electricity system with 80% clean resources can still meet demand, plus provide an 8% operating reserve margin during the highest summer and winter net load weeks, thanks to large-scale gas generation, and battery storage making up for any capacity shortfalls (Figure 14). The curtailment of RE occurred most frequently during the spring season, particularly in March and May when electricity demand was low.

Figure 14. National System Average Hourly Dispatch in 2035, with Coal Retirements



Despite the curtailment of RE, the RE share during the highest summer and winter net load weeks in 2035 (i.e., the percentage of RE contribution to overall generation) is ~36% and ~46%, respectively (Figure 15 and Figure 16).

Figure 15. National System Dispatch in the Highest Net Load Week in Summer 2035

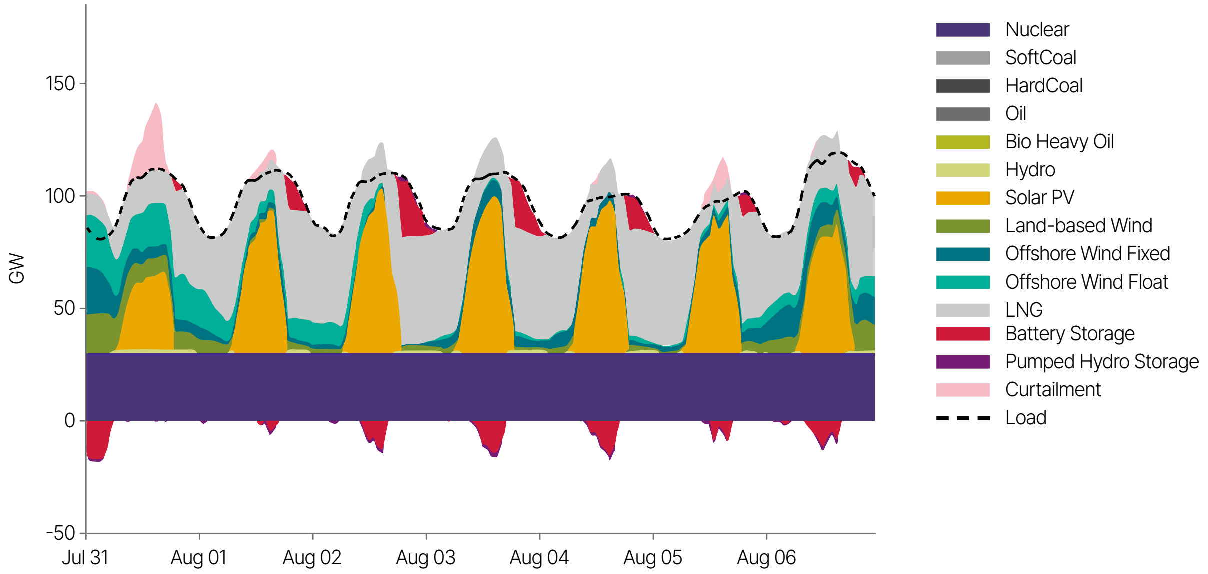
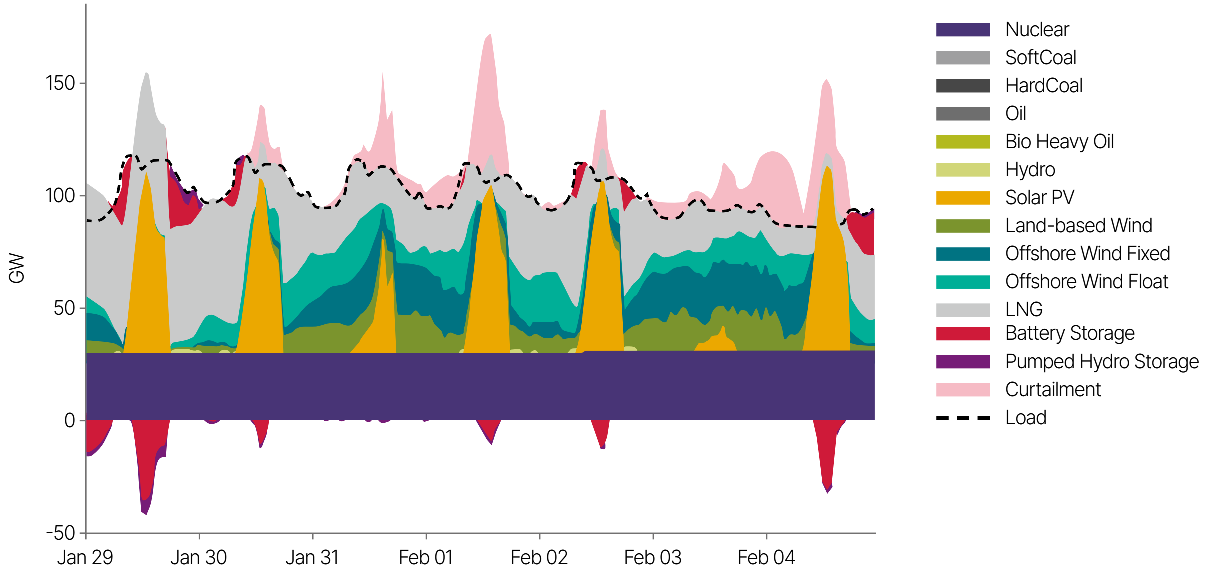


Figure 16. National System Dispatch in the Highest Net Load Week in Winter 2035



During periods of low demand in the spring and fall, a stable electricity supply was achieved. Natural gas generation was greatly reduced during these periods compared to summer and winter, and there was significant RE curtailment, particularly in spring. This indicates that the surplus energy from renewable sources exceeded what could be absorbed by energy storage systems. However, during the fall, energy storage systems were actively utilized, and there was less RE curtailment (Figure 17 and Figure 18).

Figure 17. National System Dispatch in the Lowest Net Load Week in Spring 2035

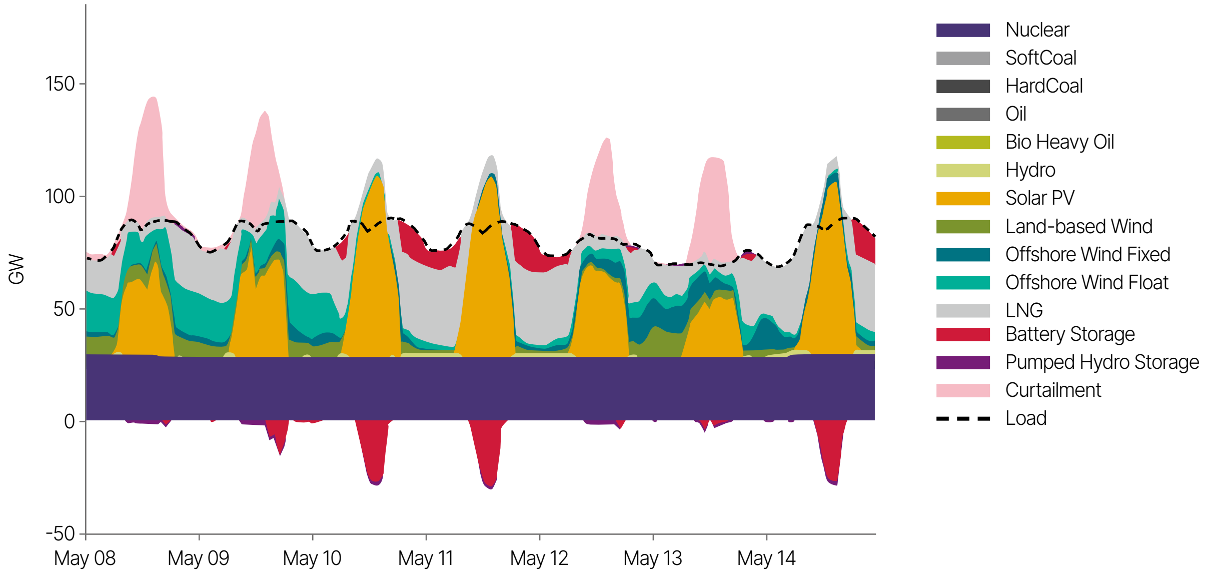
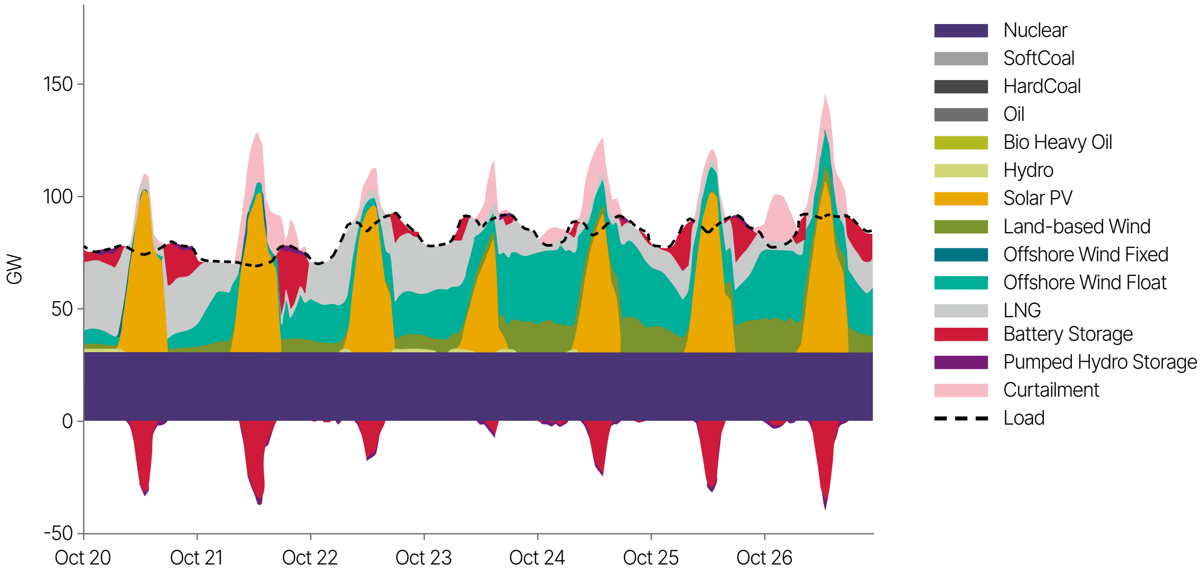


Figure 18. National System Dispatch in the Lowest Load Week in Fall 2035



Even with demand shocks, the 80% clean electricity system has adequate resources to meet unusually high demand in the peak net load week by increasing LNG generation and storage operation. With an unexpected 10% increase in demand (i.e., demand shock), peak demand increases to nearly 12 GW, but the system still has adequate resources to meet demand in the highest summer and winter net load weeks (Figure 19 and Figure 20).

Figure 19. National System Dispatch in the Highest Net Load Week in Summer 2035, with a 10% Demand Shock

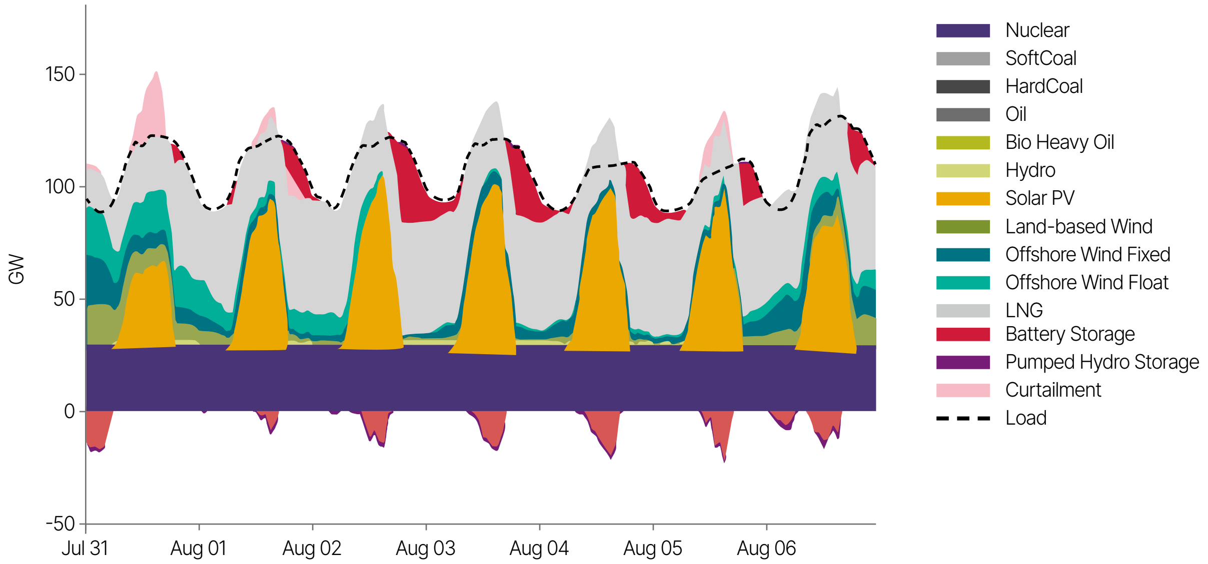
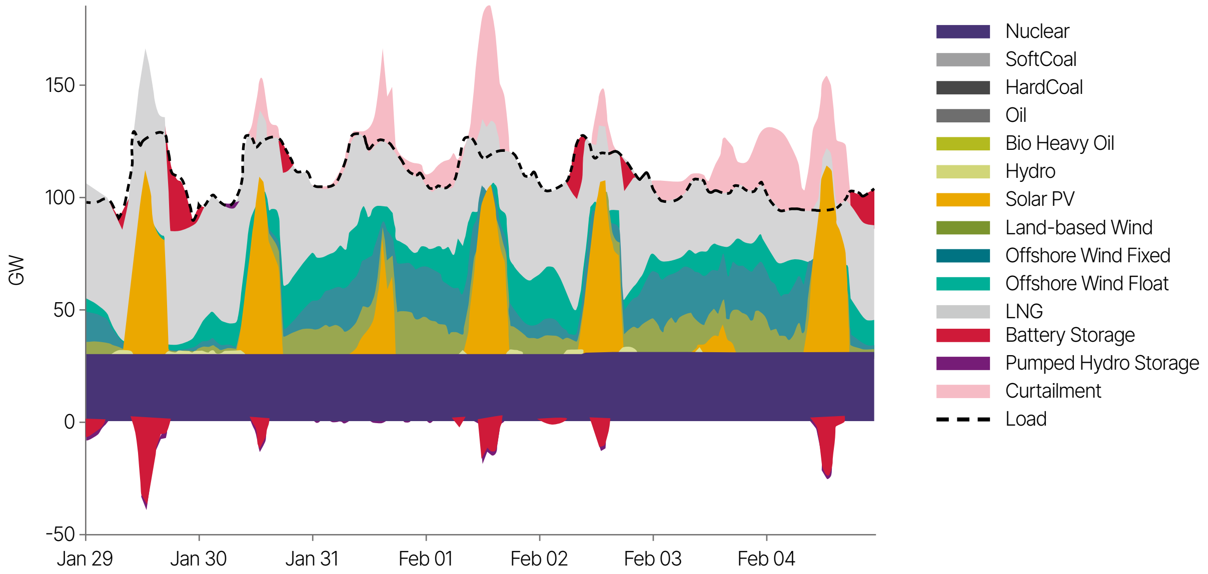


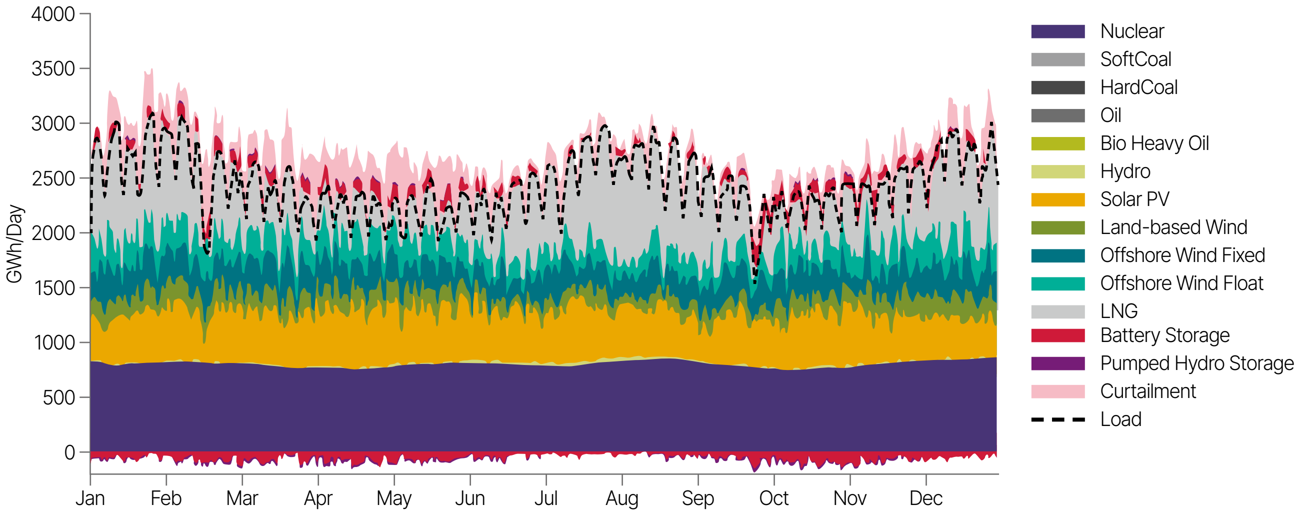
Figure 20. National System Dispatch in the Highest Net Load Week in Winter 2035, with a 10% Demand Shock



Significant Energy Storage Deployment Enables a Reliable Clean Energy Grid Despite Weather Variations

To confirm the generation mix meets system demands in every hour, even during periods of low RE generation and/or high demand, we simulate hourly operation of the Clean Energy scenario for more than 60,000 hours (i.e., each hour in seven weather years). Our results show the 80% clean generation mix from the Clean Energy scenario, including 42.3 GW of energy storage, is sufficient to meet electricity demand in 2035 (Figure 21). For all weather years, natural gas capacity requirements are highest in August, when wind generation falls significantly. Natural gas generation above 50 GW is required for fewer than 30 hours per year over the full seven-year simulation, and 19 GW of natural gas plants had a capacity factor of less than 20% (Figure 22). The low utilization rates of these gas plants could be improved by more active demand response and/or utilization of power-to-X (P2X)[8], which are not included in this study.

Figure 21. Daily National System Dispatch Averaged Over 7 Weather Years in the Clean Energy Scenario in 2035



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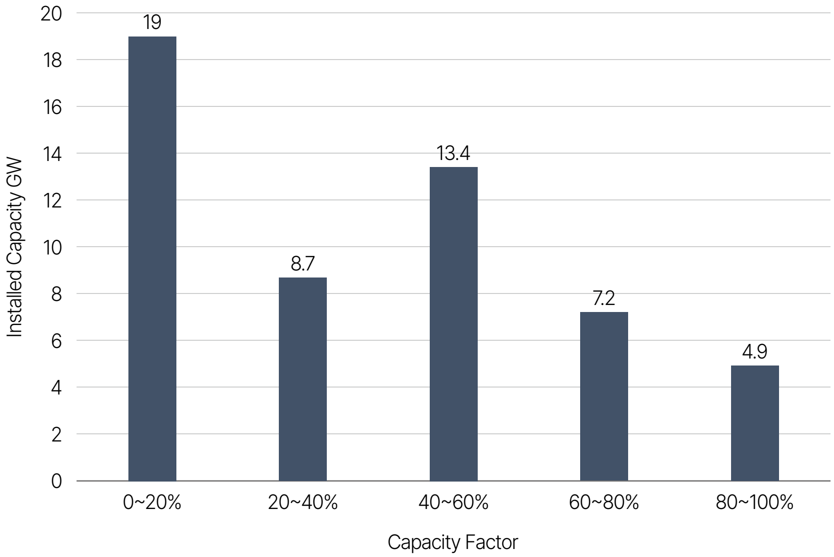
[8] P2X refers to a group of technologies that convert renewable energy into various forms of energy carriers, such as hydrogen, synthetic natural gas, and liquid fuels. The "X" in P2X represents the variable energy carrier that can be produced through these processes.

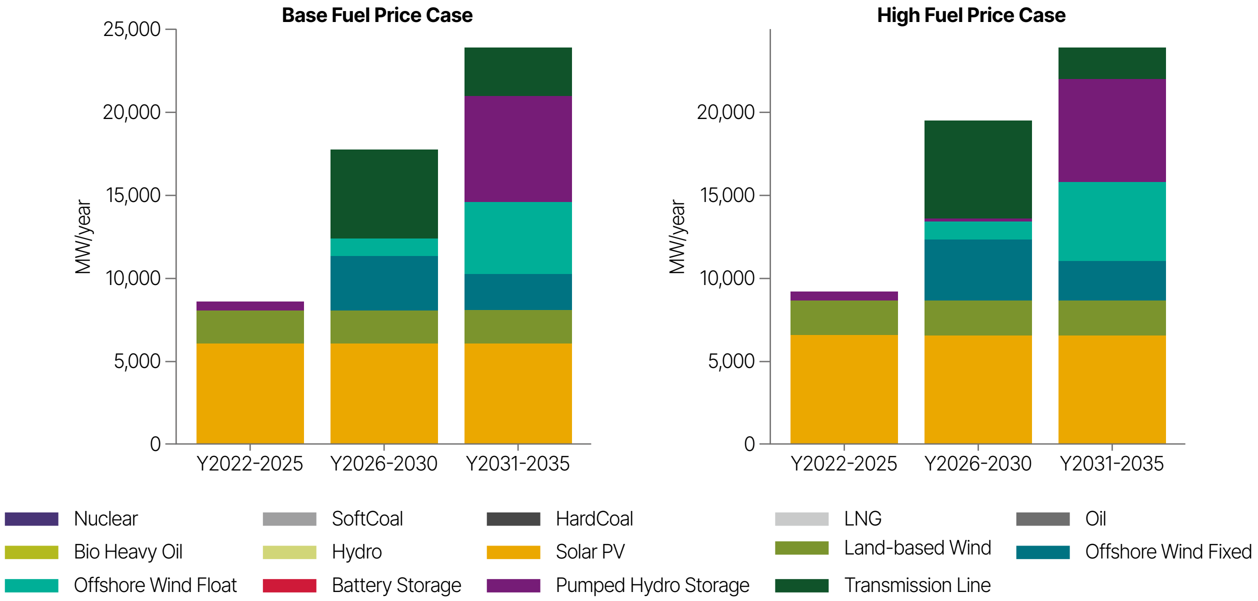
Figure 22. Installed Capacity of Natural Gas Plants by Annual Capacity Factor the Clean Energy Scenario in 2035



High Fuel Prices Accelerate and Increase Renewables and Storage Deployment

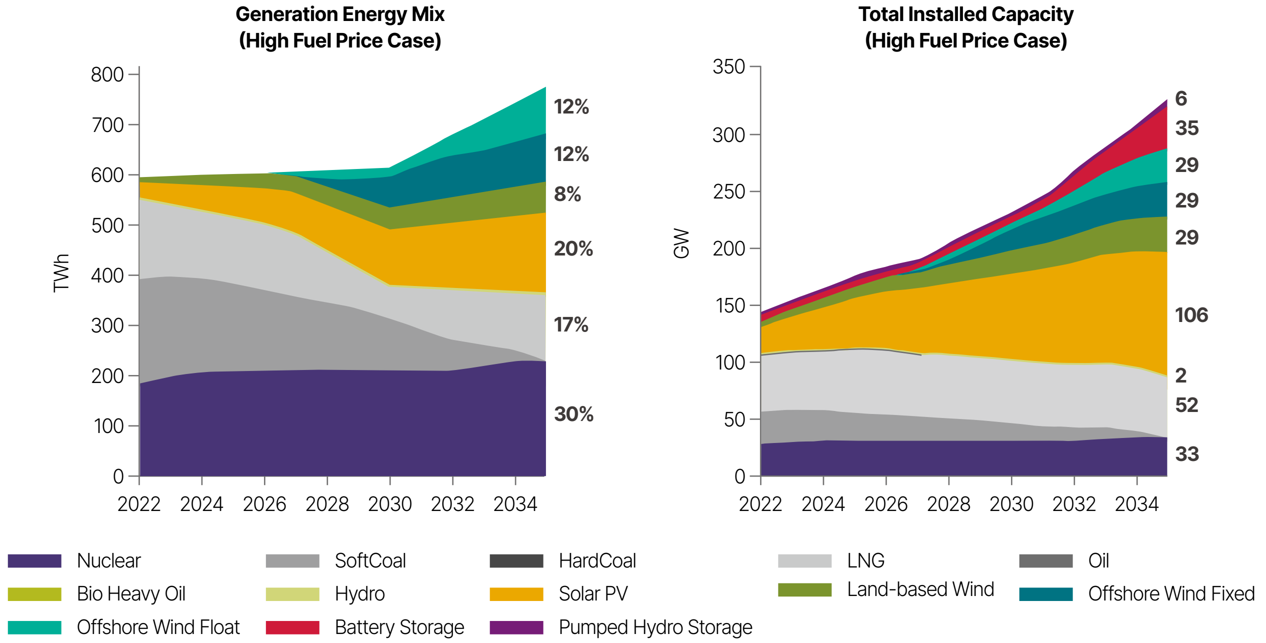
In our analysis, solar PV deploys mainly in the 2020s, while offshore wind and battery deployment ramps up significantly in the 2030s. The High Fuel price case requires earlier deployment of batteries and offshore wind, as well as more transmission to support greater renewable resources (Figure 23).

Figure 23. Average Annual Capacity Additions, Clean Energy Scenario with Base vs. High Fuel Price Cases



Under the High Fuel price case (Figure 24), solar and wind technologies become far cheaper than coal and LNG, resulting in an additional 11 GW of solar and wind by 2035, relative to the Base Fuel price case.

Figure 24. Generation Energy Mix and Total Installed Capacity Between 2022 and 2035, Clean Energy Scenario with High Fuel Price Case



In 2035, total cumulative new capital investment in generation and transmission, in the Base Fuel price case, is 120 trillion KRW. In the High Fuel price case, this figure increases by 9 trillion KRW (Figure 25). As mentioned previously, this additional investment is essentially financed using fuel cost savings.

Figure 25. Cumulative New Capital Investment in Generation and Transmission, Clean Energy Scenario with Base vs. High Fuel Price Cases

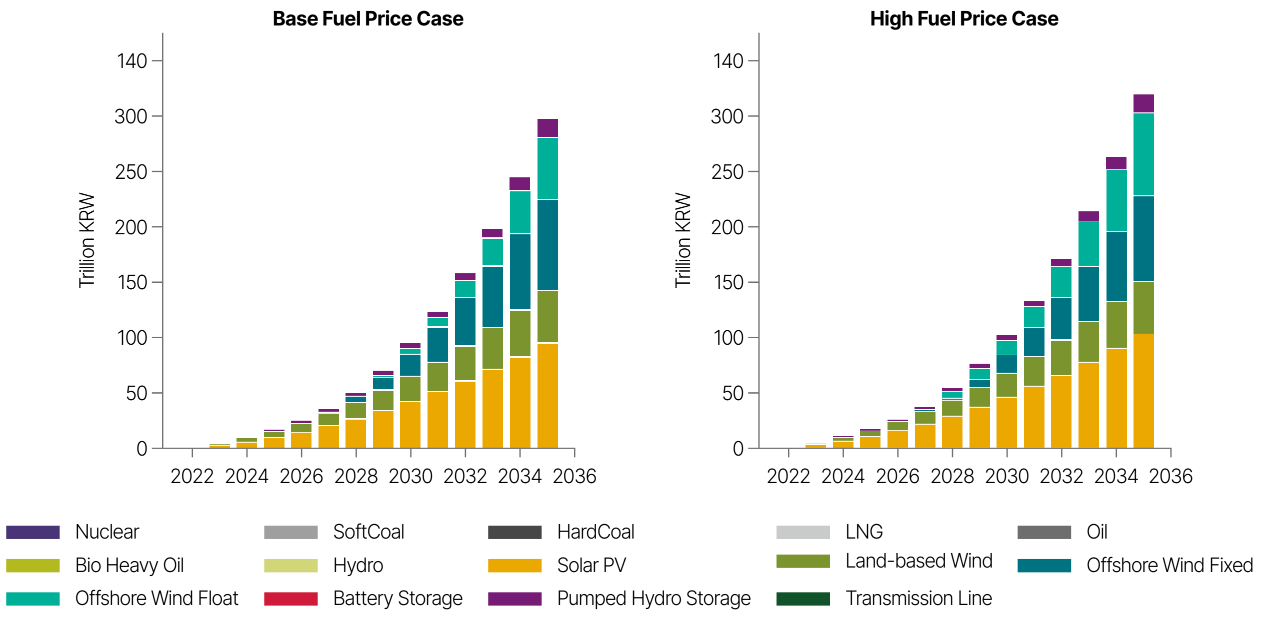
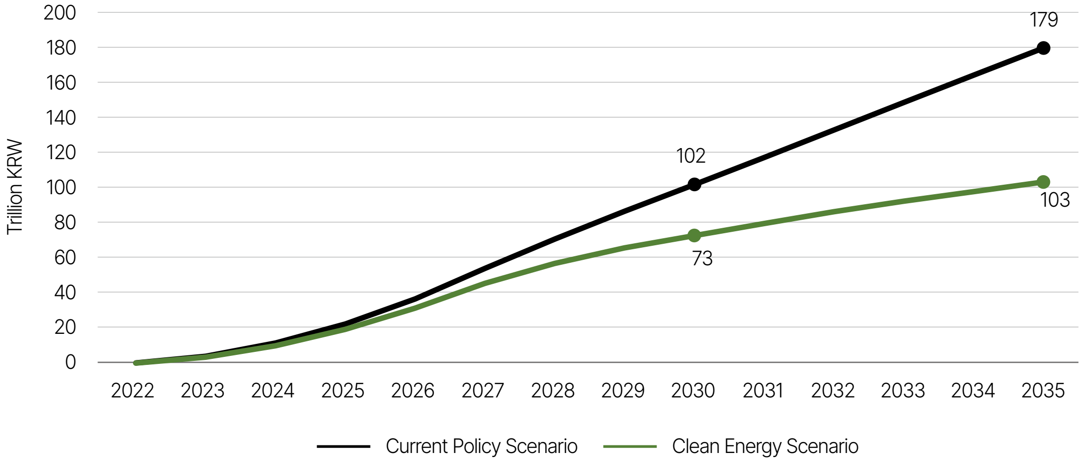


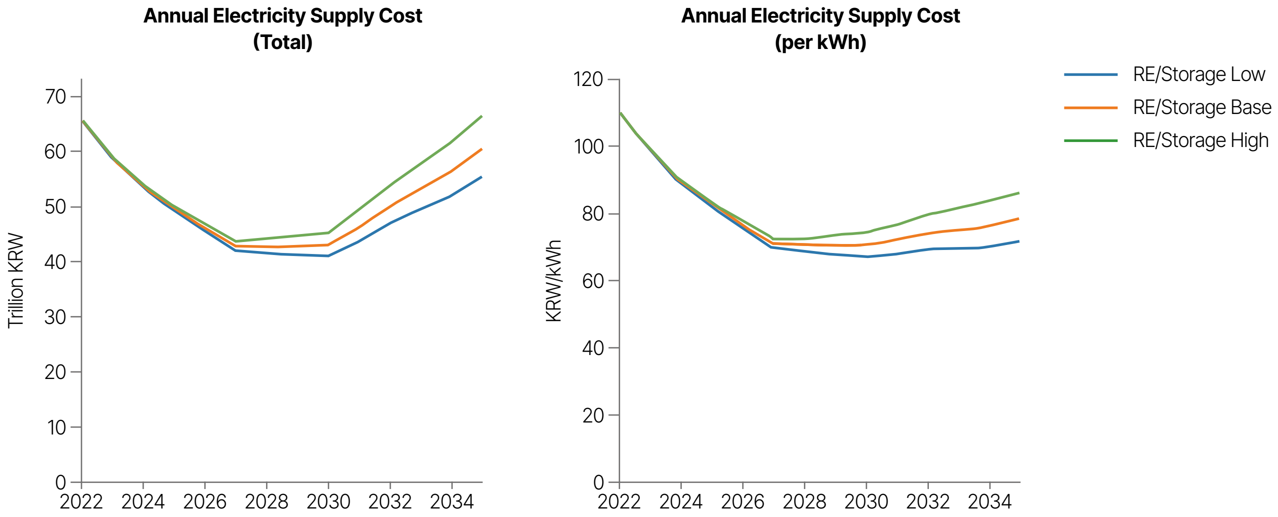
Figure 26 shows how much the Clean Energy scenario would save Korea on costs for imported fuels for power generation, relative to the Current Policy scenario, in a High Fuel price case. Using the Current Policy scenario's power mix, total incremental costs of imported fuel for power generation between 2022 and 2035 amount to 179 trillion KRW; using the Clean Energy scenario's power mix, this figure declines by 76 trillion KRW. The higher proportion of domestic renewable energy sources in the Clean Energy scenario helps Korea suppress impacts from volatile fuel prices and improves its energy security.

Figure 26. Cumulative Incremental Costs of Imported Fuel for Power Generation, Current Policy vs. Clean Energy Scenarios, High Fuel Price Case



The sensitivity analyses for Low and High RE and storage costs show that their impact on electricity supply costs ranges from a 10% increase (under High RE and storage costs) to an 8% decrease by 2035 (under Low RE and storage costs) (Figure 27). Meanwhile, the sharp increase in electricity supply costs after 2030 can be attributed to two primary factors, the first of which is growth in total electricity generation after 2030 as shown earlier (Figure 3). The second factor is the price of fuel, which increases annually from 2028 onwards (Figure 5). Notably, the effects of these cost increases on the per-unit electricity supply cost (Figure 27, right panel) are significantly mitigated by the cost savings from RE sources. This is especially true in the Low Cost RE/Storage Case, where the cost-saving effect is maximized.

Figure 27. Annual Electricity Supply Costs (Total and Per-Unit), Clean Energy Scenario, Low/Base/High RE and Storage Costs



4.
CAVEATS

Although we assessed an operationally feasible least-cost pathway of Korea's power system using weather-synchronized load and generation data, further work is needed to advance our understanding of other facets of an 80% clean power system. First, this report primarily focuses on renewable-specific technology pathways rather than exploring a full portfolio of clean energy technologies. Additionally, technical issues such as loss of load probability, system inertia, alternating-current (AC) transmission flow of both intra- and inter- regional transmission lines, and issues in AC power system such as reactive power compensation need further assessment. Options to address these issues are discussed in the accompanying policy brief, *Korean Power System Challenges and Opportunities: Priorities for Swift and Successful Clean Energy Deployment at Scale*.

Second, our assessment does not explicitly address the operational impacts of day-ahead / intra-day forecast errors in RE and load, although we did include operating (spinning) reserves in our production cost model to ensure the least-cost system has a certain capability to address such forecast errors.

The technologies and approaches examined in this report could contribute to deep decarbonization of the future electricity supply, lowering system costs while accelerating emission reductions. Although this analysis does not attempt a full power-system reliability assessment, we perform scenario and sensitivity analysis to ensure that demand is met in all periods, including during extreme weather events and periods of low RE generation. This modeling approach provides confidence that an 80% clean electricity grid is operationally feasible.

5.

CONCLUSIONS AND FUTURE ACTIONS

Sustained declines in costs for wind, solar, and energy storage technologies create new opportunities to lower electricity supply costs and reduce emissions in Korea's electricity sector. The results of this study suggest that expanding the share of clean electricity generation from 59% (under the 10th Basic Plan) and 65% (under the Current Policy scenario) to 80% (under the Clean Energy scenario) by 2035 would lower electricity supply costs and support the Korean government's goals for carbon neutrality and air quality. Transitioning to an electricity system with 80% clean energy generation would require overcoming barriers to the development and integration of wind generation, solar generation, and energy storage.

This final section summarizes the study's key conclusions, provides recommendations for changes in policy and regulation based on the results, and outlines priorities for future research identified through this study.

Declining wind, solar, and energy storage costs are changing the economics of Korea's electricity sector. The Current Policy and Clean Energy scenarios illustrate emerging changes in the economics of Korea's electricity sector. In both scenarios, the lowest-cost resources for meeting growth in electricity demand combine wind, solar, and energy storage. This finding across both scenarios suggests that the combination of these resources is more economically feasible than building new coal-fired plants or operating existing ones.

Korea's electricity system can be reliably operated with high levels of clean energy generation. Sensitivity analysis showed that Korea's electricity system could maintain high standards of reliability with an 80% clean energy generation mix that includes 50% wind and solar generation in 2035 – even during prolonged periods of low wind and solar generation and unanticipated load increases. With higher levels of wind, solar, and energy storage, reliability concerns will shift from capacity adequacy alone to combined capacity and energy adequacy. New coal generation is not needed to ensure resource adequacy.

Exceeding existing goals for clean energy generation would deliver additional emission reduction, health, and energy security benefits. Increasing the share of clean energy generation to 80% supports significant additional reductions in CO_2 emissions, health hazards, and mortality related to poor air quality. Emission reductions and health benefits would be even greater than the estimates in this study (Section 3.2) with the widespread electrification of the whole economy. For instance, transportation electrification, combined with an accelerated shift to clean energy generation to charge electric vehicle batteries, will reduce both vehicle tailpipe and power plant emissions. The combination of electrification and accelerated deployment of clean energy generation would be a powerful tool to hasten progress toward Korea's environmental goals. Further, under the Clean Energy scenario, imported coal and natural gas costs would decrease by 61.5%, from 48.1 trillion KRW in 2022 to 18.5 trillion KRW in 2035.

Reaching cost-effective levels of clean energy generation will require overcoming barriers to wind, solar, and storage development and integration. The Clean Energy scenario involves an unprecedented scale of wind, solar, and energy storage development. Wind and solar generation reach nearly 110 GW in 2030 and just over 182 GW in 2035. Energy storage grows from 6.1 GW in 2022 to 42.3 GW by 2035. For clean energy systems to be successfully added to the grid at this scale, technology will need to be more rapidly developed and integrated, requiring changes in regulations, markets, electricity system operations, and land use.

The shift to a low-cost RE pathway should begin now. The share of clean energy generation in the Current Policy and Clean Energy scenarios begins to diverge in the 2022-2025 period (Figure 7), suggesting that policy and regulatory changes to accelerate clean energy deployment are urgently needed before 2025 to trigger change. While there may be momentum for accelerated expansion of wind and solar generation, lowering remaining barriers to rapid expansion of battery storage should be made a near-term priority.

Our findings show that Korea can leverage the rapidly declining costs of RE and storage to cost-effectively deploy an additional 43 GW of renewable energy by 2035 beyond Current Policy requirements – a 31% increase in RE capacity deployed – in a way that maintains a reliable electricity grid. Accordingly, we recommend that Korea increase its 2035 deployment goals for RE and energy storage to realize significant economic, energy security, and environmental benefits while accelerating progress toward carbon neutrality and combatting climate change.

Key findings outlined above indicate challenges, policy recommendations and areas that remain for further analysis of potential strategies to achieve deep decarbonization in the Korea power sector. The accompanying report, *Korean Power System Challenges and Opportunities: Policies to Accelerate the Clean Energy Transition*, discusses these barriers and possible policy pathways in greater detail.

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APPENDIX A.
MODELING APPROACH

The state-of-the-art methodology for studies that assess the impacts of high renewable energy (RE) penetration on electric power systems is to use capacity expansion and production cost models. For this study, we use PLEXOS, an industry standard capacity expansion and production cost model, to assess the least-cost ("optimal") generation mix and inter-region transmission investments between 2022 and 2035 that meet regional electric power demand requirements, based on grid reliability (reserve) requirements, technology resource constraints, and policy constraints (Abhyankar et al. 2022).

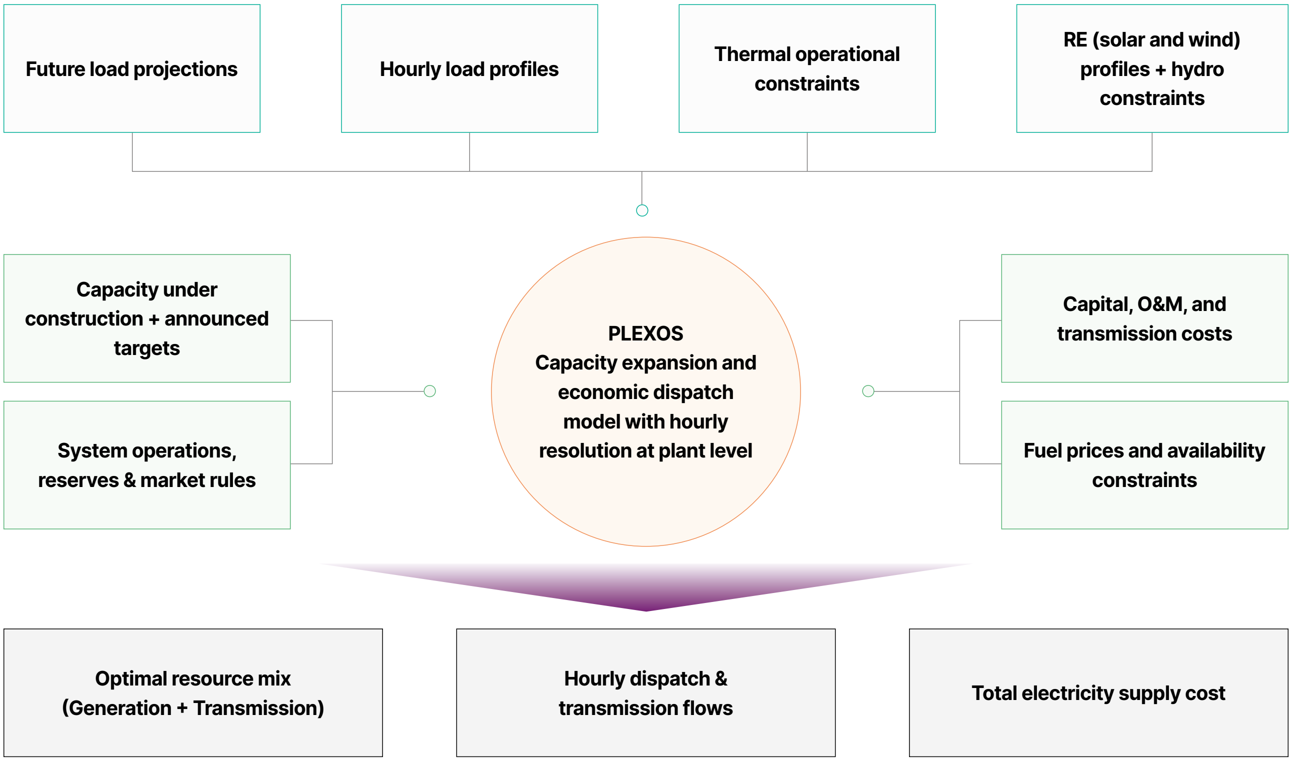
The study focuses on model years 2025, 2030, and 2035. For each year, we simulate hourly economic dispatch using the PLEXOS production cost model to ensure that the grid can run reliably for all 8,760 hours in the year, including the hours when the system is most constrained.

PLEXOS uses deterministic or stochastic, mixed-integer optimization to minimize the cost of meeting load given physical (e.g., generator capacities, ramp rates, transmission limits) and economic (e.g., fuel prices, start-up costs, import/export limits) grid parameters. Moreover, PLEXOS simulates unit commitment and actual energy dispatch for each hour (at 1-minute intervals) of a given period. As a transparent model, PLEXOS makes available to the user the entire mathematical problem formulation. The model minimizes total generation cost (fixed plus variable costs) for the entire system, including existing and new generation capacity and transmission networks (Abhyankar et al. 2022). We assess the optimal resource mix under a range of scenarios examining deployment rates, coal plant retirements, demand growth, electricity market design, demand response, and supply chain challenges.

We represent the Korean electricity grid using 11 interconnected nodes connected by 60 GW of interregional transmission corridors in 2020 (Figure 1). The transfer capacity of each inter-provincial interface is assumed to be half the sum of transmission line capacities between the two regions in order to capture the operating constraints in an AC power transmission network.

Figure A1 depicts our overall method and the various data components.

Figure A1. Overall Modeling Approach



APPENDIX B.
MODELING INPUTS

Projections of installed costs and fixed operations and maintenance (O&M) costs for land-based wind, offshore wind, solar PV, and battery storage in Korea are based on Korea's cost data and the 2022 United States National Renewable Energy Laboratory (NREL) Annual Technology Base (ATB) forecasts, and industry consultations (Lee & Kim 2020, NREL 2022). Table B1 shows the assumptions on capital costs of wind, solar and battery storage.

Table B1. Solar, Wind, and Battery Storage Capital Cost Assumptions

Year	Low	Base	High	Low	Base	High
		Solar PV			Battery storage (4-hr)	
2020	1,349	1,349	1,349	2,042	2,042	2,042
2030	731	918	1,159	649	1,005	1,249
2035	656	850	1,059	587	843	1,125
		Land-based wind			Offshore wind (fixed-bottom)	
2020	2,528	2,528	2,528	5,627	5,627	5,627
2030	803	1,237	1,309	2,316	2,855	3,537
2035	753	1,035	1,118	1,798	2,420	3,210
		Offshore wind (floating)				
2020	7,990	8,382	8,654			
2030	3,382	4,186	5,232			
2035	2,601	3,594	4,699			

- Solar and wind: thousand KRW/kW [2020 KRW (2020 USD)]
- Battery storage: thousand KRW/kWh [2020 KRW (2020 USD)]
- 1 USD = 1147 KRW (average exchange rate from 09/2013 to 08/2022)

Other clean energy costs and operational parameters have been taken from (Lee & Kim 2020), and industry consultations. Table B2 summarizes the assumptions.

Table B2. Other Clean Technology Costs and Operational Parameters

	Capital Cost*	Fixed O&M Cost*	Heat Rate (GJ/MWh)	Forced Outage Rate (%)	Maintenance Outage Rate (%)	Ramping (% of installed capacity per minute)
Biomass	2,146	29	8.3	5	10	5
Hydro		17		5	5	5
Hydrogen; Ammonia	1,006	10	6.3	5	5	4

* Capital and fixed O&M costs are in thousand KRW/kW [2020 thousand KRW (2020 USD)]. 1 USD = 1147 KRW (average exchange rate from 09/2013 to 08/2022).

Conventional technology (coal, nuclear, natural gas) capital and fixed O&M costs have been taken from NREL (2022) and (Lee & Kim 2020). Operational parameters such as ramp rates, technical minimum levels, auxiliary consumption, minimum up and down times, etc. have been taken from the data used in previous Korea and U.S. studies, regulatory norms, and expert / industry consultations. They are summarized in Table B3.

Table B3. Conventional Technology Costs and Operational Parameters

	Capital Cost*	Fixed O&M Cost*	Heat Rate (GJ/MWh)	Forced Outage Rate (%)	Maintenance Outage Rate (%)	Technical Minimum level (%)	Ramping (% of installed capacity per minute)
Coal	1,400	13	7.3	5	10	60	2
Gas CCGT	1,006	10	6.3	5	5	40	4
Nuclear	2,748	21	7.9	5	15	80	0.1

* Capital and fixed O&M costs are in thousand KRW/kW [2020 thousand KRW (2020 USD)]. 1 USD = 1147 KRW (average exchange rate from 09/2013 to 08/2022).

APPENDIX C.
SOLAR AND WIND PROFILES

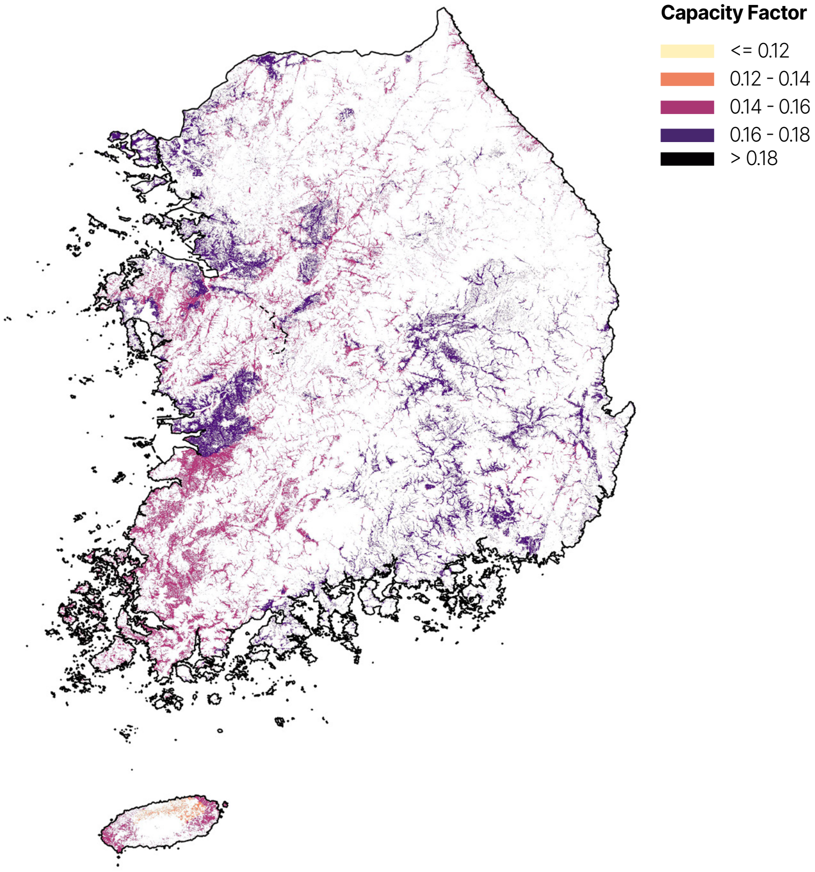
We estimated the solar and wind (offshore and land-based) resource potential and profiles from the ground up. This section explains the methodology used, which can be divided into two parts. The first part involves estimating the total resource potential of solar and wind available in each region. This forms an upper limit on the amount of new capacity that can be built in PLEXOS for each region. To estimate resource potential, we use the capacity factor data along with multiple exclusion datasets including land cover, elevation, slope of terrain, natural parks, fishery zones and defense areas. The second part involves estimating the representative hourly solar and wind profiles for each region. Profiles are estimated at the site level using meteorological data from reanalysis datasets, and then an aggregation algorithm is used to create a provincial/cluster-level representative profile. The potential and profiles are estimated at province level for land-based wind and solar, and at a cluster level for floating and fixed-bottom offshore wind.

RESOURCE POTENTIAL

Solar

To estimate the solar resource potential in each region, we start with the complete area of that region and remove the areas that are not suitable for solar development. We use four exclusion criteria for estimating the solar resource potential: land cover, slope, elevation, and natural parks. The land cover dataset comes from the European Space Agency’s Copernicus programme. We use the Moderate Dynamic Land Cover Dataset which has a spatial resolution of 100m and divides land cover into 23 classes. We exclude dense forest (i.e., forests with canopy > 70%), wetlands, moss and lichens, urban and built up areas, areas with snow and ice, permanent water bodies and open seas. In addition to land cover we use elevation and slope to remove areas not suitable for solar development. The elevation data also comes from the European Space Agency’s Copernicus programme, the Copernicus GLO-30 Digital Elevation Model. The dataset has a spatial resolution of 30m and provides elevation of the surface of earth, including man-made buildings and infrastructure. We estimate slope from the elevation dataset using the planar method. This method estimates the steepest descent based on the maximum change in elevations between the cell and the eight neighboring cells (Burrough, 1998). We exclude areas with an elevation of more than 4000m and a slope above 5 degrees. We then remove areas that fall under the territory of natural parks. After exclusions based on land cover, elevation, slope, and natural parks, the remaining areas in a region are considered suitable for solar development. To estimate the quality of solar resource potential in each region, we use resource data from Global Solar Atlas, which provides annual average solar capacity factors at 30 arcsec (~1 km) spatial resolution. This dataset and its wind counterpart, Global Wind Atlas, were developed by the World Bank. The Solar Atlas models solar generation using 10 years of meteorological data and creates an averaged solar capacity factor data. We combine the capacity factor data with the RE suitability data derived, after exclusions, to create a solar resource map of Korea (Figure C1). This map shows the capacity factor at all developable sites in Korea.

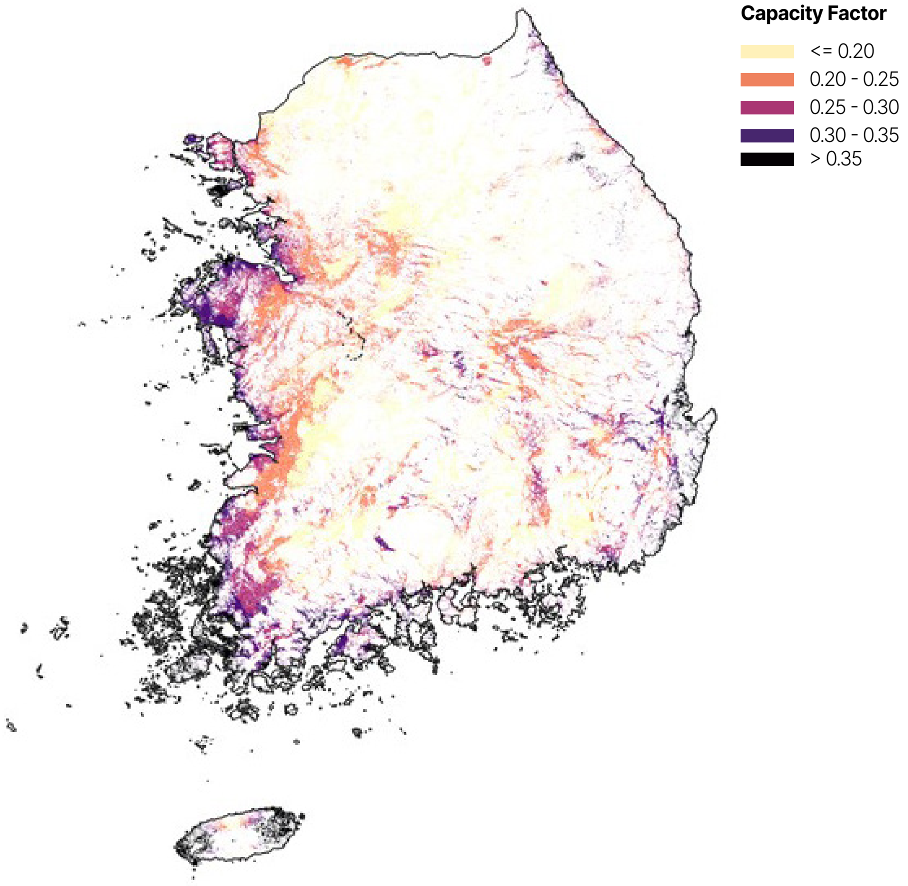
Figure C1. Developable Sites for Solar PV in Korea



Land-Based Wind

The methodology for estimating land-based wind resource potential is very similar to the method used for solar. We take the complete area of a region and remove the areas not suitable for wind development to estimate the resource potential. We use the same land cover, elevation, slope, and natural parks datasets as used for solar. However, we use different limits on elevation and slope, as solar and wind have different slope and elevation considerations. We exclude areas with elevation greater than 3000m and a slope greater than 11.31 degrees for land-based wind. For land cover, we use the same criteria as solar and remove dense forests (i.e., forest with canopy >70%), wetlands, moss and lichens, urban and built-up areas, areas with snow and ice, permanent water bodies and open seas. The Global Wind Atlas provides annual average wind capacity factors at 1 km spatial resolution. It was created using 10 years of hourly meteorological data and then averaged to get an annual average capacity factor for a site. We combine the Wind Atlas capacity factor data with our developable sites data to get a wind resource map of Korea (Figure C2). This map shows the land-based wind capacity factors at all developable sites in Korea.

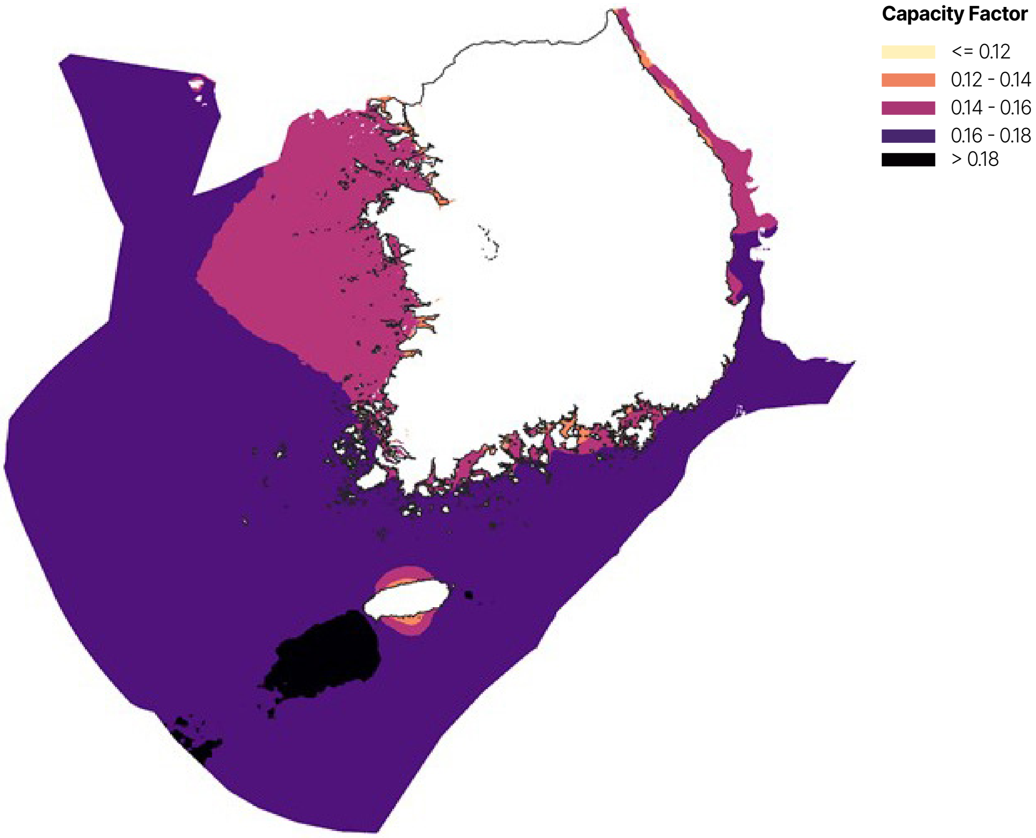
Figure C2. Developable Sites for Land-Based Wind in Korea



Offshore Wind

To estimate the offshore wind resource potential, we use the map of the exclusive economic zone (EEZ) of Korea ocean depth data, as well as GIS datasets of the locations of defense areas and fishery zones. We surprisingly know very little about the topography of our oceans, even less than the topography of Mars. The best available global bathymetry dataset is from the General Bathymetric Chart of the Oceans (GEBCO). The GEBCO dataset has global coverage with a spatial resolution of 500m. We start with a map of the EEZ of Korea and remove sites with an ocean depth greater than 1300m, assuming they are not currently economically developable for offshore wind. Sites with an ocean depth of less than 60m are suitable for fixed-bottom technology, while sites with an ocean depth of between 60 and 1300m are assumed to be suitable for floating wind technology. These limits on technology suitability are derived from NREL, which uses the same limits for the U.S. We then remove areas that fall in defense areas and fishery zones. As we did for solar and wind, we combined this dataset with the capacity factor data from the Global Wind Atlas to create an offshore wind resource map for Korea, showing the capacity factor at all developable offshore locations (Figure C3). We then develop and cluster the fixed-bottom and floating wind sites using the Multivariate Spatially Constrained Clustering algorithm. Clustering was done to keep the spatially contiguous sites with similar capacity factors in the same clusters. We then create 30 clusters for floating wind and 10 clusters for fixed-bottom offshore wind. Most of Korea's offshore wind potential is at an ocean depth of more than 60m, yielding more clusters for floating offshore wind.

Figure C3. Developable Sites for Offshore Wind in Korea



MODELING RESOURCE PROFILES

Here we describe the methodology used to create representative solar and wind hourly generation profiles for each region. We use the resource map dataset created in the previous section (i.e., the dataset with capacity factors at developable sites). In addition, we use meteorological data from reanalysis datasets. We extract wind speed, pressure, temperature, solar irradiance, etc. from reanalysis datasets and pass them through software that models wind farms and solar parks to get hourly solar and wind generation as outputs. Several sites in a region are aggregated to create a representative generation profile for each region. The methodology for solar, land-based wind, and offshore wind is discussed in detail below.

Solar

In the previous section, we created a gridded dataset of developable sites with annual average capacity factors. That gave us a technical resource potential, but not all sites that can be technically developed would actually be developed. The quality of resources drives project economics, and only the sites with the highest quality resources get developed. To get a representative resource profile for each region, we need to find a sample of the best sites and aggregate their individual profiles. To estimate the solar profile, we filter out the top 25th percentile of sites with the highest capacity factors. To ensure we do not select very low capacity factor sites, we only keep sites with capacity factors greater than 15%. From this pool of top sites in a region, we randomly select 2000 sites. We then estimate hourly generation at each of these 2000 sites and average them to create a representative solar profile for the region. Hourly meteorological data from ERA5 is used to estimate hourly generation at each of the 2000 sites (ECMWF 2020). ERA5 is an hourly reanalysis dataset from European Centre for Medium-Range Weather Forecasts (ECWMF) with a spatial resolution of 30km x 30km. ERA5 provides historical hourly data on wind speed, temperature, pressure, solar radiation, etc. at 137 pressure levels from surface up to a height of 80km. To estimate solar generation, we extract the surface solar radiation downwards (ssrd), temperature at 2m, and the u and v components of wind speed at 10m height. To model solar generation at a site, we also need Direct Normal Irradiance (DNI) and Direct Horizontal Irradiance (DHI). The ssrd variable from ERA5 gives the Global Horizontal Irradiance (GHI), and we use GHI to estimate DHI and DNI. NREL's DISC model provides empirical relationships between GHI and DHI, and GHI and DNI, based on Maxwell, 1987. NREL's System Advisor Model (SAM) is used to model solar generation. The SAM software development kit takes GHI, DHI, DNI, temperature, and the u and v wind components as inputs, and outputs solar generation. We use a single-axis system to simulate solar generation using SAM. The hourly generation at 2000 sites is averaged to create a representative profile for the region.

Land-based Wind

The methodology for estimating land-based wind profiles is very similar to solar, and a similar method is used to select sample sites in each region. We filter the top 25th percentile of sites from the annual average capacity factor dataset developed while estimating resource potential. To avoid very low capacity factor sites, we remove sites with capacity factors of less than 20%. From this we randomly select 2000 sites. We simulate hourly generation for a year for each of these 2000 sites using the SAM model. We model a wind farm with 32 turbines, arranged in an 8 × 4 rectangular shape. SAM takes wind speed at the hub height of the turbine, wind direction, surface pressure and temperature as inputs, and gives hourly farm generation as output. Meteorological data is taken from Modern-Era Retrospective analysis for Research and Applications dataset 2 (MERRA2), and meteorological data from U.S. National Aeronautics and Space Administration (NASA) (GMAO 2015). This provides wind speed at 10m and 100m, which are then scaled to the hub height of the wind turbine used; surface pressure and temperature are also available from MERRA2. For simulating wind generation, we used MERRA2 dataset which has a spatial resolution of 0.5 deg x 0.625 deg. MERRA2 data is shown to have better accuracy for wind speeds than ERA5; for this reason, we selected MERRA2 even though its spatial resolution is much lower than ERA5. To account for some of the effects of local topography, we use average wind speed data from Wind Atlas, which has a much higher spatial resolution of 1km x 1km. We create a scaling factor using the average wind speed data from both Wind Atlas and MERRA2. We scale the hourly wind speeds in MERRA2 by this factor to get a more accurate wind speed profile. Corrected wind speeds are passed through to SAM to get hourly generation. The hourly generation from 2000 sites is averaged to get a representative profile for the region.

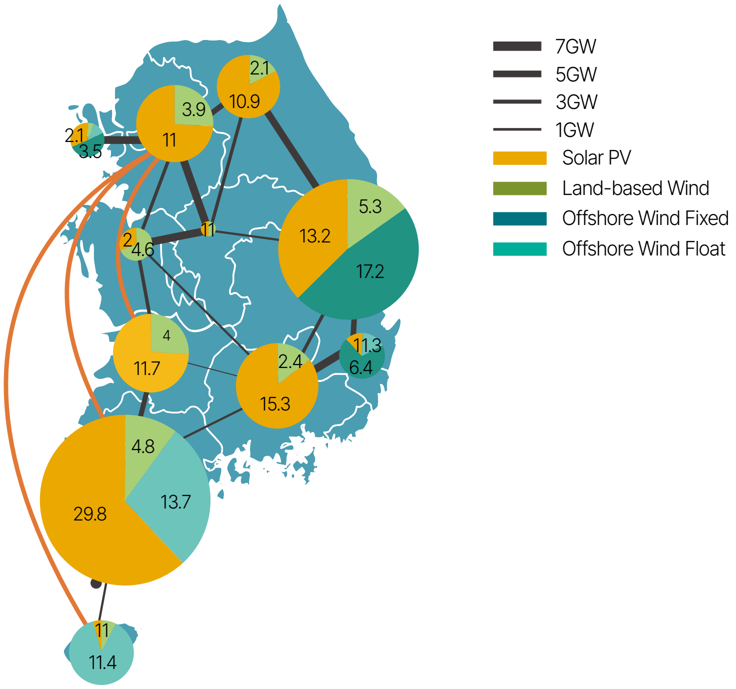
Offshore Wind

Since there are no predefined regional boundaries for offshore wind, we have to create artificial clusters to get representative profiles. We clustered the offshore wind sites into multiple clusters as discussed previously. For each fixed and floating wind cluster, we estimate one representative profile in each of the zones. To estimate profiles, we only keep sites with capacity factors greater than 40% in each of the clusters, assuming that sites with lower capacity factors are not currently economically developable. We simulate hourly generation at each site using SAM. Wind speed and direction at hub height, and temperature and pressure data are required for simulating wind generation in SAM. As with land-based wind, we also use meteorological data from MERRA2. A scaling factor is used to account for spatial downscaling, as was done for land-based wind. The hourly generation from all sites in the cluster is aggregated to create a representative profile for each cluster.

APPENDIX D.
REGIONAL RENEWABLE ENERGY DEPLOYMENT

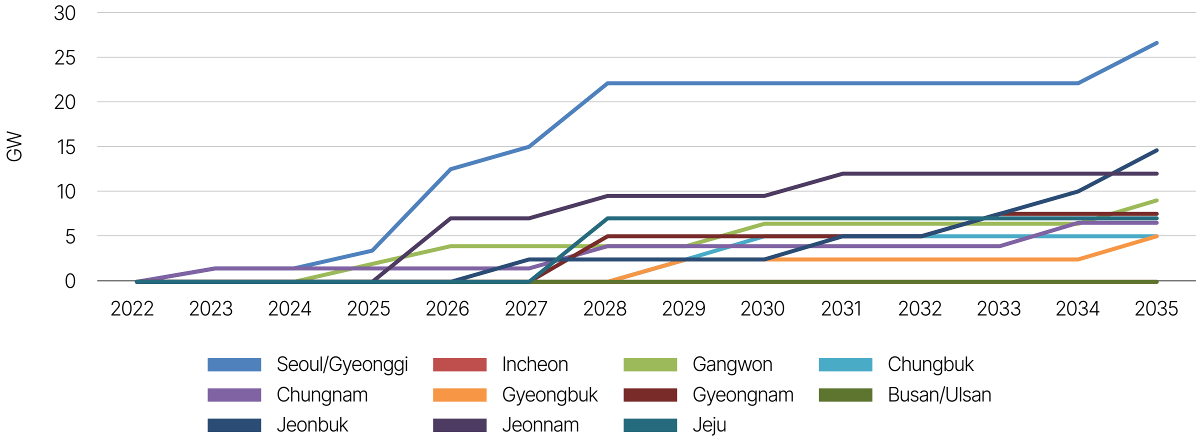
Figure D1 illustrates that renewable energy expansion in this study is concentrated in some regions, with the most prominent being the Jeollanam-do region, which accounts for 30% of all solar and 25% of wind power generation. The Gyeongsang-do region, including Gyeongsangnam-do, Gyeongsangbuk-do, and Busan, where most floating offshore wind power and 30% of solar are located, is the next most concentrated area. Fixed offshore wind is mostly distributed in Jeollanam-do and Jeju. This concentration of almost all wind and most solar power resources in the southern part of the country, combined with the concentration of electricity demand in the Seoul metropolitan area, is expected to result in a significant regional imbalance in electricity supply. The problem is exacerbated by the fact that renewable energy deployment in the neighboring Chungnam and Chungbuk regions is minimal.

Figure D1. Regional Renewable Energy Deployment by 2035 in the Clean Energy Scenario



Unlike the Gyeongsang-do metropolitan area, which has a relatively large interconnection capacity, the interconnection capacity in the Jeollanam-do and Jeollabuk-do regions is very small. Therefore, new transmission capacity is quickly saturated in the Jeollanam-do region, as shown in Figure D2. This explains why the West Coast transmission line is necessary: if it were not included in the model, the abundant renewable energy resources in the Jeollanam-do region could not be transmitted to the metropolitan area and would instead have to be moved to other regions with lower transmission utilization rates. This would increase the concentration of renewable energy in certain areas, leading to higher demand for energy storage and new transmission lines and resulting in an overall increase in costs. Therefore, the West Coast transmission line has been included in both the Current Policy and Clean Energy scenarios in the model.

Figure D2. New Transmission Capacity Installed by 2035 in the Clean Energy Scenario



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