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Korean Power System Challenges and Opportunities

Priorities for Swift and Successful Clean Energy Deployment at Scale

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ABSTRACT

With South Korea's electricity demand expected to grow 30% by 2035, transitioning to clean energy resources will be critical in reducing the electric sector emissions and achieving national climate goals. Rapid technological improvements can help keep costs low and maintain grid reliability, if Korea's government takes a coordinated approach to the clean energy transition. This policy brief identifies key barriers to Korea's shift toward clean energy, based on the authors' companion report (*A Clean Energy Korea by 2035: Transitioning to 80% Carbon-Free Electricity Generation*), interviews with experts, and the most recent data and literature. It then explores policy solutions for overcoming these technological, economic, and institutional barriers, and suggests market transformation strategies to speed the adoption of clean energy technologies. Amid ongoing cost and technological improvements in wind, solar, and energy storage, advancing this report's recommended policy actions with maximum coordination among government officials can meaningfully accelerate Korea's clean energy transition.



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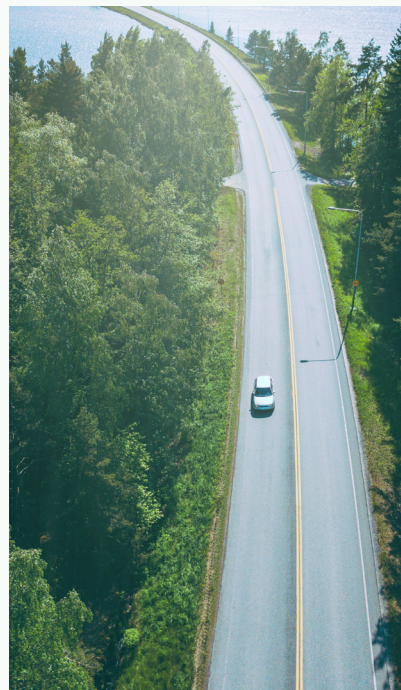
Executive Summary

Economic growth and more widespread electrification of the economy in South Korea (Korea) are expected to increase its electricity demand 31% by 2035 and 113% by 2050, compared to 2020 levels. Over that same period, Korea intends to reduce carbon dioxide emissions related to electricity generation by 80%.

Generating electricity from clean energy sources, rather than from fossil fuels, will be critical in decreasing related emissions. Continued rapid technological improvements and dramatic cost declines for solar energy, wind power, and energy storage can help encourage adoption. But policy actions coordinated across jurisdictions are needed to make this clean energy transition viable and accelerate market deployment.

To meet emissions reduction goals and rising electricity demand, while shielding itself from the volatile political and economic impacts of fossil fuel imports, Korea will need to rethink its policy on a number of fronts. Along with technical and economic factors, system reliability, energy storage capacity, grid connectivity, the power market structure, and local concerns all present distinct challenges that effective policy can help overcome.

This paper explores policy solutions and market transformation strategies needed to overcome technological, economic, and institutional barriers and fast-track clean energy deployment. The following key findings are based on research conducted for A Clean Energy Korea by 2035: Transitioning to 80% Carbon-Free Electricity Generation, interviews with experts, and the most recent data and literature. Comparisons with other countries reveal where Korean policies might find international models and new approaches Korea might consider to bolster the nation's shift to carbon neutrality.





Codified Improvements to System Standards and Grid Studies Can Maintain Reliability of a Decarbonized Power System

To ensure reliability and effectively manage the Korean power system, codified reliability standards, technical requirements, and monitoring systems must be established. As the use of fossil fuel generators decreases and the use of solar, wind, and other renewable energy (RE) sources increases, it is also necessary to identify other RE-compatible services and technical requirements for rapid response to frequency deviations.

System inertia is one measure of a power system's ability to maintain a stable frequency, but Korea's current power system reliability and electricity quality maintenance standards do not address it. A lack of system inertia can lead to an unreliable frequency in the power system and cause generators to trip, leading to power outages. Inertia monitoring and forecasting can help the Korean Power Exchange (KPX) determine the energy resources needed to maintain short- and long-term system reliability.

The KPX must maintain a specific voltage range to prevent equipment damage and system instability. Range is typically controlled using reactive power supplied by fossil fuel generators. However, as many coal- and natural gas-fired plants retire in parts of Korea, alternative sources of reactive power will be needed. Power system studies are important to accurately estimate the reactive power sources needed in each region, maintain the voltage within the necessary range, and ensure the power system remains stable.

Proactive Planning and Infrastructure Expansion Can Minimize Expected Congestion and Delays in Grid Interconnection

In Korea, there is a large distance between the regions with abundant RE resources and the areas with high electricity demand. Existing transmission capacity is limited, which could lead to severe congestion on the transmission system unless significant reinforcement occurs. An integrated study examining the size and location of RE plants, transmission lines, and reactive power sources is needed to effectively expand the transmission and energy storage networks. Network expansion will require not only infrastructure construction, but also financing options to pay for these capital-intensive projects and outreach efforts to gain public support. New technical solutions for connecting RE production areas to high-demand areas may also be useful in reducing issues related to land acquisition and community displacement.

In Korea, delays in grid interconnection are common, and most of them are due to bottlenecks in planning and implementation processes, rather than technical difficulties. Construction delays have been caused by incomplete and inadequate pre-construction studies, poorly sequenced design decisions, belated calls for vendor bids, and local opposition to projects. To minimize these delays and ensure efficient transmission planning and management, proactive decisions should be made early in the process. This can include identifying the most viable development zones and prioritizing RE projects.

Early Stakeholder Engagement Can Streamline Project Development

In Korea, the process of obtaining permits for large-scale RE projects takes twice as long as in Europe. This is often due to concerns and objections raised by local residents and organizations. To streamline project development and avoid delays, it is helpful to identify potential sources of community opposition and resistance early on and work to build consensus with these groups.

Understanding perceptions of equity, costs, benefits, and risks can help align interests and objectives across community groups, government agencies, and industry partners prior to project inception. Participatory stakeholder engagement and informed consensus building can ameliorate local concerns that might lead to opposition, including possible conflicts related to land use, environmental impacts, health and safety issues, cultural sensitivities, and disruption of economic activities.

New Tax Incentives, Procurement Targets, and Auction Designs Can Boost Market Viability

High costs are often identified as the top barrier to widespread RE deployment in Korea. Primarily due to expenses related to land, financing, and corporate taxes, Korea's levelized cost of energy (LCOE) for RE is one of the highest among major countries and second only to Japan. The lack of Korean tax incentives, combined with high capital expenditure (CAPEX) requirements, multi-criteria procurement auctions, RE certificate (REC) surpluses, and mandates for local sourcing of materials and components can jeopardize the economic feasibility of RE systems.

Tax incentives and increased procurement targets are two obvious strategies to improve RE's economic viability. Simplifying auction design, basing site-specific awards primarily on price to increase competitiveness, and designating special leasing zones for offshore wind through the use of marine spatial planning tools can boost market confidence, reduce investor risk, and avoid costly delays in permitting.





Energy Storage Financial Policies and Safety Regulations Can Lead to Improved Grid Capacity

Challenges will likely accompany the deployment, over the next decade, of energy storage systems (ESS) equivalent to 20 times Korea's currently installed ESS capacity. ESS deployment is further complicated by the fact that important government incentives ended in 2021 and were not extended. Increasing ESS capacity will require significant improvements in Korea's benefit-cost (B/C) ratios to attract investors, as well as measures to address safety concerns.

Today's low B/C ratio results from differences between REC prices and electricity bills, caps on capacity payments, and prohibitions on using ESS to support ancillary services and energy markets. In addition, numerous battery fires have made investors wary of potential liability issues.

Establishment of transparent and open regulations, along with efforts to develop markets for capacity, flexibility, and ancillary services, can make ESS competitive in the marketplace. Requiring inclusion of ESS components in Korea's national, regional, and local climate and clean energy plans can encourage development. In addition, support is needed for exploration of new ownership, business, and operational models. ESS safety requirements added to the Electrical Safety Management Act can also build public and investor confidence in the technology.

Market Reform Can Make RE More Competitive

The current cost-based pool (CBP) structure of the Korean power market can impede RE deployment because of its pricing structure, insufficient RE investment incentives, and lack of compensation for ancillary services. While this approach has been effective in minimizing overall purchasing costs, the difficulty of factoring in external costs acts as a barrier to RE deployment. Relatively low carbon prices and a high share of free carbon allowance allocation mean that the country's coal-fired generators are still highly profitable, eliminating significant incentives to shift the market to RE alternatives.

Including external costs (i.e., those incurred in relation to impacts on health and the environment, but not usually reflected in prices) through a gradual transition to price-based pools, while drastically reducing coal-powered plants' free carbon allowances, can help make RE more competitive in Korea's electricity market. Changes in the structure of carbon prices, network usage fees, economic compensation for compulsory curtailment, and incentives for flexible resources related to supply-demand balance and system stability can also make RE investment more attractive. Introducing a day-ahead, spot reserve market would encourage investments in resources vital to the success of future RE power systems, such as ESS and synchronous condensers.

To promote investment in low-carbon generators, support mechanisms such as the U.K.'s Contract for Difference (CfD) can be considered to reduce price volatility and guarantee a certain price level for electricity produced by low-carbon generators.

Reserve markets must also be established to maintain grid stability and support the integration of RE sources into the grid. These markets should comprise diverse reserve types, such as operating and regulation reserves, that are procured through competitive tendering and market-based mechanisms.

These and other policy approaches, along with international collaboration and ongoing technological innovation, will be crucial in accelerating Korea's transition to 80% clean energy by 2035.



NEXT Group is an energy and climate policy think tank dedicated to Asia's net-zero energy transitions.

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01

Introduction

Electricity demand in South Korea (Korea) is expected to increase 31% by 2025 and 113% by 2050, compared to 2020 levels, driven primarily by continued economic growth and electrification. This expected surge in demand makes the transition to clean energy even more critical for achieving carbon neutrality by 2050 (GESI et al., 2022). Significantly increasing the use of wind, solar, and other renewable energy (RE) sources to generate electricity will make valuable contributions to economy-wide decarbonization, as well as boost energy security.

The 2035 Korea Report: Strategies for Achieving an 80% Carbon-Free Electricity System (The 2035 Korea Report) shows that dramatic reductions in solar energy, wind power, and energy storage costs create opportunities to reduce emissions and overall costs related to Korea's electricity generation (Park et al., 2023). *The 2035 Korea Report's* findings suggest that cost-competitive clean energy technologies can enable Korea to achieve an 80% carbon-free electricity system by 2035, while shielding the country from the impacts of volatile international situations on the cost and supply of imported fossil fuels. Generating 80% of the nation's electricity from clean, renewable, carbon-free sources by 2035 rather than fossil fuels will put Korea's 2050 goal of net-zero carbon emissions (i.e., carbon neutrality) within reach.

Transitioning to a system that produces 80% of its electricity from clean energy sources will require widespread development and integration of wind generation, solar generation, and energy storage solutions. Although such large-scale and rapid changes in energy infrastructure pose some technical and institutional challenges, they also present opportunities to redesign the market for cleaner, more dependable, lower-cost energy.

This clean energy market transition can be accelerated by advancing policy actions and technological improvements simultaneously, with maximum coordination among government officials with jurisdiction over various types of policy. Policy solutions can help break down technological, economic, and institutional barriers to clean energy deployment.

This policy report summarizes potential barriers to Korea's clean energy transition and provides recommendations for overcoming challenges with new policies, regulations, incentives, and priorities for future research. The following pages outline issues and recommendations, based on expert consultations and prioritized by the authors' judgement, in six key areas that need support for successful clean energy deployment in Korea. Sections are ordered based on urgency and the time required to address each issue.

02

System Reliability

The transition to clean energy will require significant changes to the electricity system, pairing increased shares of solar, wind, and nuclear power with a decrease in the use of conventional fossil fueled generators. But phasing out fossil fueled generators poses reliability challenges related to system inertia, voltage service, and congestion management.

2.1 System Inertia

In Korea

In power systems, system inertia refers to the energy stored in large rotating machines that enables them to remain rotating (Denholm, 2020). Alternating current (AC) power systems are designed to operate at a specific speed, which is called system frequency. However, the system frequency fluctuates due to imbalances in supply and demand. When there is an oversupply of energy, the system frequency increases, and when there is an undersupply, the system frequency decreases.

If the frequency deviation is large, it can damage generators which are set to trip in response to such events. Tripping can lead to a system-wide blackout, which makes it important for power system operators to limit any deviation to a predefined operating range. There are control schemes on generators to retain and restore the system frequency to its nominal value, but it takes a few seconds for them to balance supply and demand. If the system inertia is too small, the imbalance can lead to frequency collapse. Thus, for the system operator, it is important to lower the rate of change of frequency (RoCoF) in units of Hz/sec (Broderick, 2018). Systems with higher inertia show lower RoCoF after a disturbance, while systems with lower system inertia show higher RoCoF.

In the past, system inertia and RoCoF were not significant concerns, because synchronous generators provided a sufficient amount of system inertia. The problem now is that these synchronous generators are fueled by coal and liquified natural gas (LNG), which jeopardizes the attainment of Korea’s carbon neutrality goal. As RE generation increases, these fossil fueled generators will be decreased or phased out altogether – and RE systems do not offer an alternate supply of system inertia.

Recent research estimates Korea’s maximum RE capacity with its current power system at merely 21 gigawatts (GW) due to a shortage of system inertia (KPX, 2020a; see Table 1). At the same time, *The 2035 Korea Report* estimates the nation will require 182 GW of RE by 2035 to meet its carbon-reduction goals. To bridge this gap, the 10th Basic Plan for Long-term Electricity Supply and Demand (BPLE)¹ addressed the addition of 54 GW of system inertia by 2036, which will enable the Korean power system to incorporate more RE sources.

Table 1. Estimated Minimum Inertia, Reserve Capacity, and Maximum RE Capacity in Korea’s Power SystemE

	2021	2022	2023	2024
Minimum inertia (GWs)	359	365	351	359
Inertia constant	3.63	3.67	3.58	3.62
Reserve capacity (MW)	5,199	5,180	5,501	5,072
Maximum RE capacity that current power system can support				~21 GW

Source: KPX (2020a)

Korea’s power system reliability and electricity quality maintenance standards define criteria including reserve requirements, operating voltage ranges, and generator frequency operation – but not system inertia or RoCoF.

Fortunately, in 2019, the Korea Electric Power Corporation (KEPCO) patented a system that can be combined with the existing supervisory control and data acquisition system to monitor inertia (KEPCO, 2021). Although the system currently is used only to measure system inertia, it is expected to provide additional functions, such as system planning considering system inertia, as clean energy grows.

¹ The BPLE, Korea’s comprehensive documentation of electricity regulations and plans, includes basic principles of electricity supply and demand, long-term forecasts, power system planning, and demand-side management. The BPLE is updated every two years, most recently in January 2023, covering the period of 2022-2036.

In the United Kingdom

United Kingdom transmission system operator (TSO) National Grid ESO (NGESO) recently introduced Dynamic Containment, a new service that can supply both real inertia via rotating machines and synthetic inertia with a fast response to frequency deviations. These inertia resources can help maintain frequency within the statutory range of +/-0.5 hertz in the event of a sudden spike in demand or generation loss.

NGESO plans to power this service with clean energy. Eight wind turbines supporting system inertia were launched in the summer of 2022 (NGESO, 2022a). Five synchronous condensers and five grid-forming converters, which reduce the need for inertia by conventional fossil-fueled generators, are slated to start operation in 2024 (SEI, 2022). NGESO is also deploying GE's Effective Inertia Forecasting & Metering Solution to measure and forecast system inertia.

In Australia

The National Electricity Rules require the Australian Energy Market Operator (AEMO) to periodically estimate and publish inertia requirements for each subnetwork (AEMO, 2020). AEMO's recent assessment indicated that additional service for system inertia will be necessary if the generation mix is changed to include a higher percentage of clean energy. It is expected that three out of five regions would undergo a shortfall of system inertia before 2025. In response to the assessment, Australian inertia service provider ElectraNet announced plans to procure 200 megawatts (MW) of upward raised fast frequency response (FFR) and 110 MW of lower FFR services that help control power system frequency following contingency events, particularly during periods of less inertia (ElectraNet, 2022).

In Finland

Finland transmission system operator Fingrid, a member of the European Network of Transmission System Operators, published data on the inertia of the Nordic power system (Fingrid, 2020). Preparing for a future low-inertia system, an FFR service was implemented in 2020. Because FFR is needed during periods of lower system inertia, Fingrid has shared information on the required amount of FFR and procures FFR in its day-ahead hourly market.

Recommendations

System inertia and RoCoF should be defined as part of codified reliability standards and combined with requirements for established technical specifications, monitoring systems, and forecasting capabilities. This will enable KPX to manage these items in a continuous and systematic way.

Standards need to identify services capable of supplying grid inertia, including real rotating machines and synthetic inertia resources. Technical requirements for inertia resources also need to be defined. For example, the Primary Reserve, the fastest reserve service currently defined in the Korean power system, must respond to frequency deviations within 10 seconds. The resources supplying inertia should be faster than the Primary Reserve.

Solutions need to include forecasting as well as monitoring functions. To help the KPX decide which energy resources to activate to keep Korea's power system reliable, forecasting should estimate future grid inertia spanning from a few seconds to a few years. A multi-year inertia forecast will help the KPX decide when, where, and what amount of grid inertia resources are required. This long-term forecast should consider the impacts of increasing clean energy and decreasing synchronous generators. In addition, system inertia should be managed separately in the two areas where synchronous inertia is expected to continue (i.e., the Korean mainland and Jeju Island).

2.2 Reactive Power and Voltage Service

In Korea

Power equipment is designed to operate in a certain voltage range, making it important for power system operators to maintain voltage in the correct operational range to meet the needs of utilities and customers (Kundur, 1994). Voltage lower or higher than the proscribed range can lead to grid instability and equipment damage.

AC power systems generate both active power and reactive power. Active power is used to light lightbulbs and run motors, and more, while reactive power helps establish and sustain the electric and magnetic fields required by AC power equipment such as motors and inverters. Positive active power increases voltage levels, and negative active power decreases voltage levels. Reactive power is provided or absorbed by sources such as generators, synchronous phasors, and capacity banks.

Voltage is more sensitive to reactive power than active power, so reactive power can be used to control voltage more precisely in the needed operational range. High voltage levels can be lowered by absorbing reactive power, and low voltage levels can be raised by generating reactive power. This voltage control using reactive power is called “voltage service.” Conventionally, the majority of this voltage service is supplied by fossil-fueled generators, such as those powered by coal and LNG.

According to the 10th BPLE, Korea will decrease its share of coal generation to 19.7% by 2030, down from 34.3% in 2021. To accomplish this, six older coal-fired power plants that have operated for more than 35 years have been phased out since 2020, while 28 newer coal-fired generators with a total capacity of 14 GW are planned to be converted to LNG upon reaching 30-35 years of operation.

In Korea, coal-fired generators are concentrated in the Chungnam, Gyeongnam, Incheon, and Gangwon regions. As presented in Table 2, Chungnam not only has the largest number of coal-fired generators (29, with a total capacity of 18 GW), but it is also home to 75% of the generators planned for LNG conversion in the next decade. If coal-fired generators are phased out, these regions will need alternative reactive power sources to maintain voltage security.

Table 2. The Number of Coal-Fired Generators by Selected Regions

Regions	All coal-fired generators (2023)		Old coal-fired generators ^a (+ 20 running years in 2036)	
	The number of generating units	Capacity (MW)	The number of generating units	Capacity (MW)
Chungnam	29	18,246	9	5,100
Gyeongnam	14	8,200	2	1,000
Gangwon	7	4,674	1	1,022
Incheon	6	5,080	4	3,480
Jeonnam	2	699	2	699
Total	58	36,869	18	11,271

^a The 28 generating units scheduled for conversion from coal to LNG are excluded from this count. Source: MOTIE (2023)

Regions with high RE potential will also need voltage service to maintain voltage levels in a certain range. In Korea, although electricity demands are concentrated in the northern metropolitan areas, the RE potential is concentrated in distant southern regions such as Jeollanam-do (Jeonnam) and Gyeongsangnam-do (Gyeongnam). While *The 2035 Korea Report* might indicate that increasing RE in these southern regions would be economically efficient, the need to transmit this electricity to high-demand areas hundreds of miles away would raise voltage levels in regions such as Jeollanam-do and Gyeongsangnam-do.

If the voltage profile cannot maintain the operating range at the needed voltage level (i.e., 139 kV [kilovolt]–169 kV for a 154kV system), the power system will experience instability. To maintain voltage levels in the predefined operating range, additional reactive power sources will be required in these regions.

In the United Kingdom

In the U.K., a study by NGENSO estimated the required amount of voltage service and prioritized the regions most in need of voltage services (NGESO, 2021). The resulting report identified seven regions with potential high voltage problems due to the high penetration of RE, which collectively are projected to lose access to 4,600 megavolt-ampere reactive power (MVAR) of reactive capacity by 2030 through plant closures. Other potential problems include occasional low overall demand, along with low regional demand compared to the high anticipated output from RE.

In addition, NGENSO is trying to estimate the potential for establishing additional reactive capability across England and Wales (NGESO, 2022b; NGENSO, 2022c). The system operator is also demonstrating the world's first regional reactive power market in real systems (NGESO, 2022d), which could incentivize voltage service providers and help secure the required reactive power supply.

Recommendations

Korea still needs to conduct voltage requirement studies that explore its future power mix. As in the U.K., additional voltage service resources will likely be required for multiple Korean regions where a large number of coal-fired power facilities are being phased out and there is widespread integration of RE. The requirements specific to individual regions and prioritization across regions also need to be studied.

03

Congestion Management and Grid Interconnection

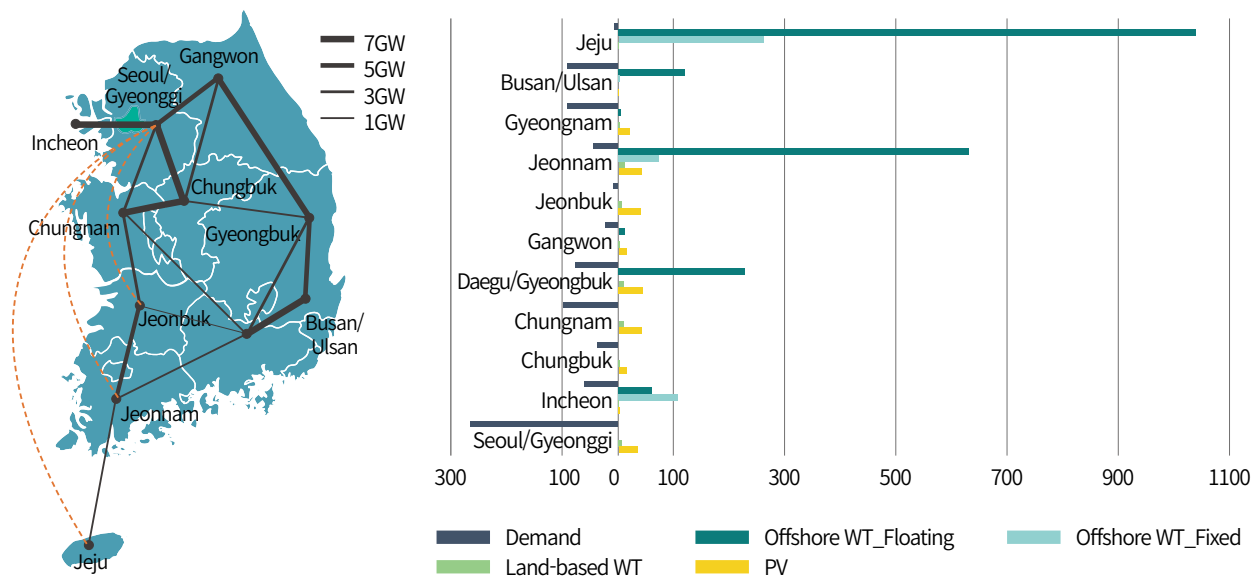
3.1 Congestion Management

In Korea

Congestion of transmission lines poses one of the most challenging barriers to increasing RE. In Korea, electricity demand is mainly concentrated in the northern Seoul/Gyeonggi area, where half of the nation's population lives (see Figure 1). But the greatest potential for RE is concentrated in the southern part of the country, and transmission capacity is limited.

RE development is already concentrated in Jeonnam and Jeonbuk, generating 32% of Korea's RE in 2019. This concentration will become even higher, with plans for 56.5% of the nation's new RE installations to be located in these two regions.

Figure 1. 2035 Projected Regional Demand and RE Potential



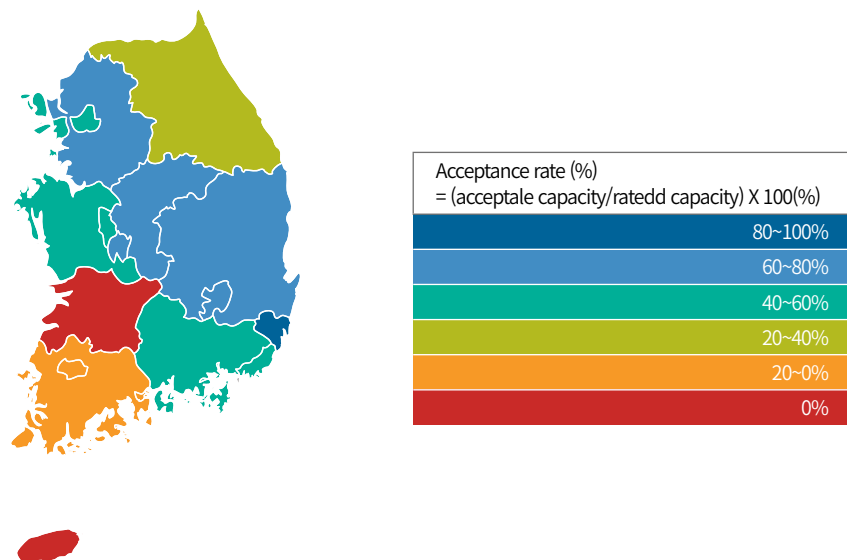
Source: Park et al. (2023)

The amount of RE capacity that can be added to a system, beyond its existing RE capacity, is referred to as the “acceptable capacity”. “Acceptance rate” refers to the portion of acceptable capacity that can be connected to existing rated capacity. A higher acceptance rate means a substation is capable of connecting more RE systems, while a lower acceptance rate indicates that there is limited capacity for additional RE systems. Adding new transmission lines or new non-wires alternatives can help increase the acceptance rate in areas with lower rates.

Figure 2 shows regional RE acceptance rates, taking into consideration congestion based on the existing transmission system (KEPCO, 2022). Each 154 kV substation has a rated capacity at the upper limit of the RE capacity that can be handled by the substation.

The figure shows that the Jeonnam and Jeonbuk regions appear to have no capacity available to accept additional RE. This means that these regions are unable to connect more RE sources due to limitations in today's transmission system.

Figure 2. RE Acceptance Rate (Acceptable Capacity Over Rated Capacity) By Region



Source: KEPCO (2022)

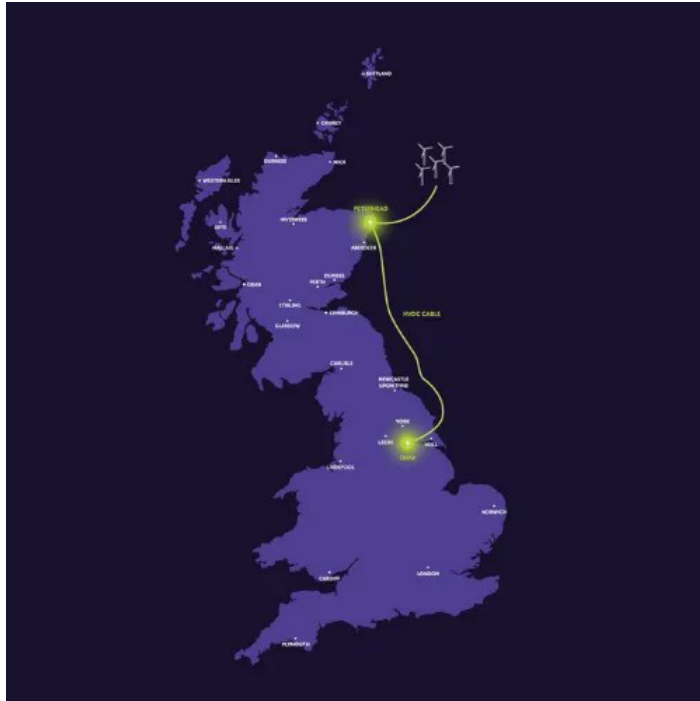
In the United States

In the U.S., the Department of Energy (DOE) launched a \$2.5 billion Transmission Facilitation Program (US DOE, 2022) to help construct new transmission lines and related facilities to connect more RE to the power grid. The program is expected to support the development of new and upgraded high-capacity lines through three financing options: capacity contracts, loans, and public-private partnerships.

In the United Kingdom

While the United Kingdom has strong potential to develop successful wind power plants off the coast of Scotland, its greatest electrical demand is concentrated in England. To connect these two points, U.K. energy market regulator Ofgem has approved high-voltage direct current (HVDC) electricity transmission projects (Skopljak, 2022; Trendafilova, 2022). The initiative includes a subsea electricity highway connecting Peterhead, in Scotland, to high-demand areas in England. This transmission line is expected to increase RE supply and displace fossil fuel consumption in the United Kingdom.

Figure 3. The Plan for the British 2 GW Subsea HvdC Transmission Line Connecting an Offshore Wind Farm in Peterhead, Scotland, to High-Demand Areas in England



Source: Trendafilova (2022)

Recommendations

Resolving the line congestion expected to result from additional Korean RE generation will require large-scale reinforcement and expansion of the transmission system. Methods of reinforcement include constructing new transmission lines and adding energy storage capacity. In some cases, transmission line construction has been delayed due to local opposition. Directly connecting subsea HVDC lines from RE production areas to demand areas can help circumvent these issues, an approach that is assumed in the analysis of *The 2035 Korea Report* (Park et al., 2023).

3.2 Grid Interconnection

In Korea

According to *The 2035 Korea Report*, an additional 60 GW of transmission capacity is needed between metropolitan areas and areas with plentiful RE resources to accommodate additional RE generation.

In Korea, delays in grid interconnection have been common since the establishment (October 2016) of, in October 2016, of a policy guaranteeing acceptance of grid connections for solar and wind systems of 1 MW or less. Through June 2020, only 29% of connection requests have been approved, representing only 12% of capacity as shown in Table 3. A large portion of delays has occurred in specific regions, such as Jeolla-do and Gyeongbuk, due to the high volume of requests in these areas. These delays highlight the need to expand power network facilities in order to accommodate RE development.

Table 3. Transmission Grid Access Requests Between October 2016 and June 2020

	Transmission Access			
	Requested	Completed	Stand-by	% of completion
Number of requests	801	233	568	29%
Capacity (MW)	18,995	2,292	16,703	12%

Source: KEPCO and MOTIE (Kim, 2021)

In the process of expanding existing facilities, KEPCO has encountered opposition from local residents to the installation of utility poles, transmission towers, substations, and transmission lines. These objections led to delays in the construction of power facilities and the interconnection of RE systems. In response, KEPCO has implemented alternative approaches.

One of these approaches was to increase the regulated acceptable capacity of RE on each distribution feeder. Prior to 2020, feeder capacity was set at 10 MW; in 2021, it was gradually increased to 13 MW. Also, the minimum level of demand of the distribution feeders was considered to increase the acceptable capacity. These efforts have led to a decrease in stand-by capacity due to scarce power facilities to 3 GW as of September 2021. However, this approach may not be sustainable in the long term, given the need to interconnect more than 100 GW of RE sources. Ultimately, installing additional power facility infrastructure will be the solution, although this will require significant time after grid access is requested.

Interregional power line construction, which is necessary to accommodate large power plants, also has suffered delays. For example, the Dangjin 9 power plant has been unable to operate at full capacity due to the delay in the construction of the Dangjin-Bukdangjin transmission line. Although the HVDC East Coast-Singapyeong transmission line was originally scheduled to be completed before the start of commercial operation of Shinhanul 1 and 2, the Gangneung Anin coal-fired power plants, and the Samcheok coal-fired power plants, the bidding process to select a transmission construction company did not begin until 2022. Although the chosen HVDC cabling requires 10% less of a safety zone around the transmission towers compared to a 765 kV AC transmission line, construction has still been delayed.

In a previous BPLE, power plant locations and construction schedules were determined first, and only then were transmission lines considered based on the power plant schedules.

This approach has led to inevitable delays in grid interconnection. To avoid delays in the future, it is necessary to expand grid interconnections in advance, factoring in the congestion that is expected to result from the growth of RE systems. The 10th BPLE plans to construct grid interconnections in areas where congestion is expected due to variations in electricity generation by geographical region. This can help ensure that future RE projects will be connected to the grid on the schedule needed to meet clean energy goals.

In the United States

A recent U.S. study shows that most grid connection delays are due to market-based barriers, rather than faulty generators (Rand et al., 2022). Certain U.S. regional grids, such as the PJM regional market, have experienced connection delays due to structural bottlenecks.

The PJM regional grid coordinates wholesale electricity in the eastern United States across 13 states (Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia) and the District of Columbia. The PJM market is traditionally defined by low RE adoption and systems designed for large natural gas power plants. A sudden proliferation of applications from small RE projects has caused a severe backlog of grid interconnection applications (Bruggers, 2022).

To address these processing delays, PJM has proposed a phased solution that includes a two-to-three-year pause on new project reviews and the formation of a task force to finalize longer-term system reforms. The task force will help prioritize projects that are closest to ready for construction and discourage those that are more speculative or lack full financing (Bruggers, 2022).

In contrast, Texas' Competitive Renewable Energy Zone (CREZ) represents successful management of rapid RE capacity growth and related surges in demand for grid connection. Texas designated zones and engaged stakeholders in formulating transmission optimization plans for development of large-scale wind resources and power delivery to load centers (Americans for a Clean Energy Grid, 2021). This proactive approach to planning for future transmission growth avoided grid connection delays (Shiraishi et al., 2023).

At the national level, the U.S. Federal Energy Regulatory Commission (FERC) also began a process of seeking public comments to identify potential reforms in longer-term regional transmission planning and cost allocation. This effort anticipates future generation needs while rethinking cost responsibility for regional transmission facilities, interconnection-related network upgrades, and enhanced transmission oversight (FERC, 2021)

Recommendations

Experience in the U.S. indicate that earlier proactive transmission planning and management, rather than reactive measures taken in response to pressing concerns about energy economics (congestion) or reliability (facility age), can help minimize grid connection delays. Such a proactive approach can include establishing qualified RE zones, making suitable topography and land-use designations, and engaging stakeholders at early stages in developing plans for large-scale RE development, transmission optimization, and power delivery to load centers.

04

Local Priorities

In Korea

A large-scale RE project such as an offshore wind power plant faces a lengthy and uncertain permit application process in Korea. Although the actual construction timeline might be similar to that found in Europe (i.e., three years), the total permit application process in Korea takes six years. Legislation is being discussed to reduce processing time and complexity.

In addition to dealing with bureaucratic logjams, project developers often encounter opposition from local residents and organizations. Communities can be wary of large-scale RE projects in their backyards, no matter how much individuals might theoretically support national clean energy efforts. RE developers should try to gain a comprehensive understanding of local issues and priorities to reduce friction that can affect overall project success and community acceptance (Lee et al., 2020).

Local concerns related to large-scale RE projects can be classified into three categories:

- Encroachment on areas used for other economic activities, such as fishing, agriculture, recreation, and tourism
- Environmental and health impacts, including potential harm to the ecosystem, habitat disruption, noise and light pollution, and excessive water consumption
- Failure to give local residents a sufficient voice in the decision-making process

Conflicts with the local fishing industry are the main challenges for large-scale offshore wind power projects. A recent study revealed that the lack of communication between developers and local communities was a crucial reason for project delays in a Tong-Yeong offshore wind project (KEI, 2021). The developer, local governments, and other regional authorities neglected to include local stakeholders, who were concerned about potential effects on the fishery industry and the community as a whole, in early stages of discussion. Although compensation was offered later to address these issues, the community deemed the amount insufficient. This example illustrates how important it can be for developers to establish a dialogue with local communities from project outset.

Solar photovoltaic (PV) installations typically draw greater acceptance from surrounding communities than do wind power plants (Lee et al., 2020). Opposition to large-scale solar PV projects is usually based on environmental concerns such as deforestation, landscape degradation, and ecosystem loss (Park et al., 2019). Given that half of the agricultural land in Korea is leased (KOSIS, 2022), the increase in land value that often results from large-scale solar PV development can drive up rental costs to the point they become burdensome for tenant farmers (Lee, 2022).

In the United States

Reasons for local opposition to RE projects in other countries closely mirror those found in Korea. In the United States, in addition to the environmental, land use, and community input concerns already identified, disputes have also cropped up from issues related to land values, construction site safety, soil quality, and alignment with religious and cultural values. In addition, jurisdictional disagreements about regulatory authority and difficulties in reaching consensus on acceptable impacts of proposed projects have arisen among local, regional, and federal governments and agencies (Susskind et al., 2022).

In E.U. Countries

Similar sources of local opposition to RE projects have also been observed in the E.U. Local conflicts between onshore wind developers and residents concerned about biodiversity protection have led areas of Germany to adopt stringent local laws that govern the siting of new wind projects in relation to residential buildings based on wind tower height (Zimmermann, 2022).

If a certain species of bird identified by the E.U.'s nature protection law is found on a planned wind project site, the development will be prohibited. In the Netherlands, unaligned local livability interests, regional landscape protection interests, and national RE objectives have resulted in conflicts related to wind projects (Koelman et al., 2021).

In China

In China, possible conflicts between conservation and agricultural land-use priorities remain areas of concern for new RE projects (Abhyankar et al., 2022).

Recommendations

In light of these identified sources of potential opposition and resistance, there is a strong need to address community concerns early in the project development process, keeping in mind local perceptions of fairness, costs, benefits, and risks (Climate Policy Info Hub, 2022). In addition, ensuring alignment of interests and objectives across multiple tiers of government in advance can also help reduce the possibility that competing priorities will hamper RE development.

Early participatory stakeholder engagement and informed consensus building efforts can help mitigate local concerns that lead to opposition. Integrated resource planning can help alleviate potential land-use conflicts and reduce environmental impact concerns.

05

Technical and Economic Feasibility

In Korea

High costs of RE sources are often the first barrier mentioned when assessing the potential for wider deployment of RE in Korea. While *The 2035 Korea Report* highlights the expectation that clean energy deployment will decrease electricity supply costs, the levelized cost of energy (LCOE) for RE in Korea is the highest of all major countries except for Japan (Table 4).

However, the overnight capital cost of commercial solar PV is not significantly different between Korea (\$1,240/kW) and the United States (\$1,357/kW) (IEA, 2020). Overnight capital cost consists of capital expenditures that would be incurred if a plant could be constructed overnight. These calculations exclude construction period financing, while including costs of onsite electrical equipment, a nominal-distance spur line, and necessary upgrades at a transmission substation (NREL, 2022).

Discrepancies between the Korean and U.S. LCOE for RE are mainly due to factors such as higher Korean land costs, financing costs, and corporate taxes. For example, Korea's limited land area results in high land costs, raising the LCOE of solar PV.

Although the corporate tax rate is higher in the U.S. (25.7%) than in Korea (22%), generous U.S. tax incentive programs provide a 30% investment tax credit to offset the total cost of installing RE generators. Moreover, the RE developer can use a complementary mechanism such as tax equity investor (TEI) if low profits rule out some other tax benefits in a given year.

Korea implements the Special Taxation for Including Depreciation Cost of Assets Invested in Plant and Equipment in Deductible Expenses scheme, which is comparable to the Modified Accelerated Cost Recovery System in the United States. Similar to the U.S. investment tax credit, the benefits of the Korean scheme are concentrated at the early stages of development. However, in Korea:

- All corporations are required to pay minimum tax, and the minimum tax cannot be reduced by any tax benefits
- Korea has no tax benefit transfer mechanism such as TEI
- The special taxation scheme cannot be carried forward to next year

This combination of factors makes it impossible for RE developers in Korea to fully benefit from tax incentives.

Table 4. LCOE and Overnight Capital Cost by RE Sources for Each Country

RE sources	Korea	U.S.	Denmark	France	Australia	Japan	China
Utility Solar PV							
LCOE (\$/MWh)	96.56	44.00	43.56	33.94	37.06	172.05	50.68
Overnight capital cost (\$/kW)	1,240	1,357	847	850	882	2,006	730
Onshore Wind							
LCOE (\$/MWh)	113.33	38.90	29.18	56.08	43.00	140.17	58.37
Overnight capital cost (\$/kW)	1,982	1,319	918	1,475	1,432	2,282	1,174
Offshore Wind							
LCOE (\$/MWh)	160.98	65.56	45.09	89.82	85.36	200.18	81.82
Overnight capital cost (\$/kW)	3,520	2,060	1,721	3,069	3,474	4,039	2,265

Unit: USD per MWh for LCOE, USD per kW for overnight capital cost

Source: IEA (2020)

In the case of wind power, Korean CAPEX and LCOE are still higher than those found in other countries, although *The 2035 Korea Report* projects these expenses will decrease over time. This expectation is due to a number of factors related to Korea's domestic wind industry being less technologically mature than that of other countries.

For example, Korean domestic suppliers have little experience in manufacturing key components such as wind turbines and monopiles (AEGIR et al., 2021). Korean commercial-scale wind turbines also have shorter rotor diameters and smaller capacities than wind turbines produced elsewhere. As a result, the LCOE of wind power plants made with domestic Korean components is higher than those with foreign components.

Competitive bidding for long-term wind power contracts (referred to as “wind auctions”) is scheduled to start at the end of 2023, and will be awarded in large part based on bidders' contributions to the domestic industrial ecosystem, investments, and job creation (KEA, 2022). Regulations mandating local sourcing of materials and components may jeopardize the economic feasibility of Korean wind power plants.

The multi-criteria auction is one of the unique characteristics of Korean RE procurement. It applies not only to wind auctions as mentioned above, but also to solar PV auctions. This approach generally requires higher support costs than price-only auctions (del Rio & Kiefer, 2021). Solar PV auctions in Korea require carbon footprint certification to reduce the lifecycle carbon emissions related to solar PV modules. Analysis has shown that the multi-criteria RE auction model, paired with carbon footprint certification for PV modules, resulted in a 4.5% increase in total support costs (Lee et al., 2022). Since carbon footprint certification accounts for 10 out of 100 points in solar PV auction scores, the cost increase is likely greater in wind auctions, where 24 points are allocated for carbon footprint certification.

RE generators in Korea earn profits by selling electricity in the wholesale market and RECs to mandatory renewable portfolio standards (RPS) suppliers. Although the spot price of RECs temporarily increased in 2022, it has fallen by more than half since 2017.

The main factor in this decrease is REC oversupply. The supplier needs to submit the mandatory supply of RECs, which is determined by RPS mandatory supply rates multiplied by the total previous year's electricity generation (excluding RE generation). During the period of falling REC prices, RPS mandatory supply rates increased by merely 1% per year, while the issuance of RECs has experienced a 23% compound annual growth rate for the last five years. Moreover, the average REC weighting benefit increased from 1.07 in 2012 to 1.67 in 2020, as the government expanded the scope of RE subject to the benefit and also increased the level of the benefit.

These policies increased the REC surplus and deteriorated renewable developers' profitability. In recognition of the situation, laws were amended to increase the upper limit of RPS mandatory supply rates to 25% and increase yearly RPS mandatory supply rates.

In the United States

In the United States, offshore wind projects with construction beginning between 2017 and 2025 are eligible for an investment tax credit of 30% of expenditures. This supports the U.S. goal to install 30 GW of offshore wind capacity by 2030. Multiple federal agencies are coordinating on plans to advance new lease sales through swift review of construction and operation plans, allocating \$230 million for port and intermodal infrastructure, and providing \$3 billion in debt capital for offshore wind development (U.S. White House, 2021).

At the state level, Massachusetts and New York have adopted offshore wind procurement mandates of 1.6 GW by 2027 and 2.4 GW by 2030, respectively (NCSL, 2020). In 2021, the Massachusetts procurement target for 2030 was increased to 5.6 GW to support new state goals for CO2 emissions reduction and carbon neutrality (Ford, 2021). Maryland designated RECs for offshore wind of up to 2.5% of the state's electricity supply. In addition, Maine, Maryland, New Jersey, and Oregon have developed specific offshore siting and permitting policies.

In Other G7 Countries

The United Kingdom and other G7 countries including Canada, France, Germany, and Italy, have historically used auctions to support the development of offshore wind. France first awarded six offshore wind projects with government-guaranteed contracts to sell electricity at high tariff rates. Public opposition and changes in domestic industry development plans eventually led France to cut rates by over one-third, from \$240/MW USD to \$150/MW USD (IRENA, 2018).

In Germany's first auction, three out of four winning projects did not require additional support beyond wholesale electricity prices. The second round of German auctions, in 2018, had higher prices, with winning projects given 25-year operating permits and a guaranteed grid connection financed by electricity consumers.

The United Kingdom plans to hold Contract for Difference auctions every two years, with a total budget of \$740 million USD to support the government's goal of adding 2 GW of offshore wind per year in the 2020s (IRENA, 2018).

In China

China dropped its guiding price for feed-in tariffs for offshore coastal wind power twice in six years and announced plans to end its feed-in tariff subsidy in 2022 (Gao, 2020). After setting a target to have 10 GW of offshore wind capacity under construction by 2020, China exceeded that goal by connecting an additional 16.9 GW of offshore wind capacity to the grid by the end of 2021 (Weekes and Richard, 2022).

Recommendations

Based on international approaches, two specific recommendations for promoting offshore wind include: first, designating offshore wind farm zones, using marine spatial planning tools to identify and create leasing zones that provide market confidence, reduce investor risk, and avoid delays in permitting; and second, simplifying auction design and making site-specific awards primarily based on price to increase competitiveness of offshore wind technology and reduce investor risk (IRENA, 2018).

06

Grid Energy Storage

In Korea

Since 2018, the total capacity of all energy storage systems (ESS) connected to the Korean power system has reached 1.6 GW and 4.8 GWh (NARS, 2021). In terms of power capacity, 40% of ESS are used for peak load reduction, 36% in hybrid systems (i.e., a combination of RE and ESS), and about 24% for frequency control. Most ESS are part of government pilot projects.

The government tried to increase the installation and usage of ESS by introducing the following support programs systems in the 2010s (NARS, 2021):

- Hybrid systems combining ESS with wind power or PV receive four to five times the RECs issued to a standalone ESS
- Consumers equipped with hybrid systems qualify for a discount on their electricity bills
- Buildings used by public institutions with a peak demand over 1 MW are required to be equipped with an ESS capable of storing more than 5% of the peak demand
- ESS' categorization as high-efficiency energy equipment makes them eligible for an investor tax deduction

However, the provision of higher RECs for hybrid systems equipped with ESS ceased in 2021. Furthermore, the installation of ESS in public buildings has been delayed, with only 20% of the 353 buildings where ESS are required having installed them by September 2022 (KS, 2022). These delays have been attributed to battery fires that occurred in 2018 and 2019 (YNA, 2022). After the fires, Korea's Ministry of Trade, Industry, and Energy organized a public-private joint committee to investigate the causes, which were determined to be:

- Insufficient systems protecting batteries from electric shocks
- Inadequate operating environment management
- Careless installation
- Insufficient ESS-integrated control and protection systems

Subsequently, the Electrical Safety Management Act has been amended to incorporate additional ESS safety requirements. Despite the decrease in support programs and increase of regulations, ESS continue to be regarded as important power facilities for Korea's power system. In the 10th BPLE, 3.7 GW (2.3 GWh) and 22.6 GW (125 GWh) of short- and long-duration storage are required by 2035, respectively. Furthermore, according to *The 2035 Korea Report*, Korea needs 42.3 GW/182 GWh of energy storage by 2035. It is expected that challenges will accompany this large addition of ESS, which will involve deploying 20 times the currently installed ESS capacity over the next decade.

Increasing ESS capacity by 2035 will require sufficient profits for ESS investors, which are not possible in today's environment. According to several studies focusing on the economic value of ESS in Korea today, the benefit-cost (B/C) ratio is estimated to be one or less (KEMRI, 2019; KDI, 2015).

One of the reasons for the low B/C ratio is that ESS income mainly depends on the difference in the price of RECs and electricity bills over time, rather than income from the electricity market. Further, an ESS cannot be used to support ancillary services and energy markets. For the ESS to be profitable through arbitrage, negative prices in the electricity market would be required.

In the United States

The United States has codified requirements for energy system operators to allow full participation of ESS resources in energy, capacity, ancillary services, and wholesale markets.

As of 2022, nine U.S. states have set energy storage targets, and many are investigating market mechanisms and/or incentives to support these targets (Plautz, 2022). California was the first state to enact legislation to develop energy storage targets in 2010, followed by Oregon in 2015. Nevada's 2017 state legislation directed the setting of biennial energy storage procurement targets for certain utilities, followed by the establishment of statewide targets of 100 MW by 2020 and 1,000 MW by 2030 (Shields, 2020). Other states including Massachusetts, New Jersey, New York, and Washington have included explicit roles or targets for energy storage in their statewide climate and clean energy plans.

In E.U. Countries

In the European Union, a revised electricity directive aims to increase market competition and ensure fair access by preventing transmission and distribution system operators from owning or operating energy storage facilities. The same directive bars utilities from making decisions about energy curtailment that discriminate against customers with behind-the-meter ESS. The European Investment Bank also committed to lending €1 billion to ESS projects in 2020. The E.U. Innovation Fund supports the demonstration of low-carbon technologies and includes specific funding for ESS (Walstad, 2020).

Markets designed by E.U. members Italy, Portugal, the United Kingdom, and Ireland allow storage operators to bid for contracts that provide fixed and predictable revenue streams in return for commitments to storage capacity in future years. Italy awarded capacity payments to energy storage operators for the first time in November 2019, with a total of 95 MW storage capacity committed for delivery in 2022 and 2023 (Walstad, 2020).

In China

In China, provincial governments provided initial policy support for ESS. Shangxi, Hunan, Qinghai, Henan, Inner Mongolia, Xinjiang, Anhui, and Jiangxi issued policies requiring new wind projects to install energy storage devices.

At the national level, China announced near- and mid-term targets for different types of energy storage, including 30 GW from new battery storage technologies by 2025 and 120 GW from pumped hydropower by 2030. This was followed by a mandate from China's National Energy Administration that from 2021 on, new solar and wind projects must include ESS capacity equal to 5-20% of the RE system's capacity. This is intended to drive investments in ESS despite unfavorable economic returns in China's highly regulated power market, where large state-owned utilities are considerably more likely to take on uncertainty and risks (Wood Mackenzie, 2021)

Recommendations

Based on international experience, policy recommendations to support the development of grid energy storage include: first, allowing ESS (particularly batteries) to participate in forward and spot markets, with goals to create stable business models and allow buyers and sellers greater flexibility in determining optimal ESS use, siting, and ownership; and second, providing direct support for ESS through mandates and policies.

Direct support remains the most common incentive for deployment, but the greater emphasis should be placed on other enabling conditions. Making regulations transparent and open, and developing markets for capacity, flexibility, and ancillary services can make it possible for ESS to compete with other technologies and measures that provide energy system flexibility (Kamiya et al., 2021).

07

Market Reform

In Korea

The current structure of the Korean power market can impede implementation of the clean energy transition presented in *The 2035 Korea Report*, due to its pricing structure, insufficient RE investment incentives, and lack of compensation for ancillary services. The Korean power market is a cost-based pool (CBP) market in which dispatch priorities are given to the cheapest generators. In the CBP, the market price, called “system marginal price” (SMP), is determined by the marginal variable cost at which marginal demand is incurred. This pricing structure makes generators lower their variable costs to receive higher priority in the market.

If the pricing system is only based on variable cost, it is difficult to account for other significant factors, such as fixed costs and environmental external costs. Thus, additional rules are needed to reflect the factors in the market price. For example, coal-fired generators have lower variable costs than LNG-fired generators but have higher environmental costs, such as higher emissions of carbon and fine dust. In the conventional CBP, coal-fired generators get priority over LNG-fired generators because of their lower variable costs. However, with an additional rule considering carbon emissions, higher priority could be given to power sources with lower carbon emissions. This kind of dispatch mechanism considering environmental cost is called “environmental dispatch.”

The Korean power market has already implemented environmental dispatch considering carbon emissions, but the relatively low carbon price (compared to Europe) and a high share of freely allocated carbon allowances (about 90%) have limited its effect on the dispatch order (MOE, 2020). Consequently, coal-fired generators still can make sufficient profits in the Korean electricity market, eliminating the incentive to reduce carbon emissions and hindering low-carbon resources from entering the market.

The Korean power market does not provide sufficient investment incentives for potential RE investors. The RE business requires huge initial investments that are recovered over many years, making it vulnerable to electricity market price fluctuations. By contrast, a direct power purchase agreement (PPA) enables a RE electricity supply operator to sell electricity directly to consumers without going through the power market. Unfortunately, high network usage fees that drive up the unit price of a direct PPA by as much as 1.91 times the industrial electricity rate (SFOC, 2021) have thus far resulted in only two PPAs under contract in Korea (KEA, 2022).

Curtailment is another factor that hinders brisk RE investments in Korea. Recently, rapid increases in RE have led to several instances of oversupply in Jeju Island, increasing the curtailment of wind power (KPX, 2020b). Economic compensation was not given for this compulsory curtailment, and no pricing mechanism existed for the curtailments. Curtailment will occur on mainland Korea on a far larger scale as the deployment of RE increases. Without reasonable compensation or market mechanisms, curtailments will greatly hinder investment in RE.

In the current electricity market, there is not sufficient compensation for resources, such as energy storage systems and synchronous condensers, that contribute to supply-demand balance and system stability. As fossil-fuel-based synchronous generators that supply inertia and reactive power are replaced by REs, the need for balancing resources will increase. However, market mechanisms providing adequate economic compensation for these resources do not yet exist. For example, energy storage systems cannot make a sufficient profit, as there is not enough price difference in the Korean power market for arbitrage. Also, as mentioned earlier, the electricity price is not affected when there are oversupplies, leading to RE curtailment. In most electricity markets, the electricity price is negative when RE curtailment occurs, which enables ESS to get paid even while charging. The absence of negative pricing makes it harder for ESS owners to get more profit and recover their investment costs in Korea's power market.

Furthermore, while synchronous condensers can help reduce must-run fossil-fueled generators by supplying reactive power and inertia, there are no settlement rules for them due to the absence of an ancillary services market. Fortunately, the 10th BLPE envisions the establishment of real-time and ancillary service markets, which would improve the profitability of these resources. Advanced market mechanisms in other jurisdictions can also help accelerate the decarbonization of the Korean power market.

In the United Kingdom

U.K. Electricity Market Reform (EMR) was introduced to balance the priorities of meeting increased electricity demand and decarbonizing the power sector (DECC, 2011). The Carbon Price Floor (CPF) was established to set the lower limit of carbon prices, which increases every year. As a result, the price of coal power generation rose sharply and became less economically feasible as it was pushed out of the dispatch priority order. Due to CPF, coal generation sharply decreased, as did carbon emission intensity (DBEIS, 2019, 2018).

Contract for Difference (CfD) is a system for uncertainty in RE revenue. This support method promotes low-carbon generator investment by reducing price volatility and guaranteeing a certain price level for electricity produced by low-carbon generators (DBEIS, 2020).

U.K. electricity regulator Ofgem temporarily issued a generation license to a synchronous condenser to promote grid stability. This synchronous condenser is considered a pathfinder in the rapidly changing power system (Ofgem, 2021).

In the Nordic Countries

NordPool is a power exchange operating in several Northern European countries. The NordPool market facilitates the trading of electricity through various trading periods, including day-ahead, intraday, and real-time markets, enabling market participants to manage their electricity supply and demand in real time. Negative prices in the NordPool market arise when the supply of electricity surpasses demand, causing the electricity price to fall below zero. This trend is not limited to the regional scale but has been observed at the system-wide level due to the significant increase of REs (ERR, 2020).

In the United States

In U.S. power markets, the price of electricity is determined through a bidding and offering process. Negative electricity prices may arise due to local congestion of the transmission system, resulting in an excess of supply over demand in the affected region, or due to a system-wide oversupply of electricity (Seel et al., 2021). This negative pricing can provide price signals to flexible energy suppliers and consumers. Large flexible energy consumers can benefit from such scenarios by taking advantage of abundant and affordable energy supply to lower their costs (Seel et al., 2020).

In the U.S., reserve markets are commonly found within regional transmission organizations (RTOs) and independent system operators (ISOs), which have the responsibility of overseeing the transmission grid and ensuring dependable and effective electricity distribution to end-users. The reserve market is composed of diverse reserve types, including operating and regulation reserves, that are procured through competitive tendering and market-based mechanisms. For example, PJM operates a Synchronized Reserve Market, Non-Synchronized Reserve Market, and Secondary Reserve Market in both Day-Ahead and Real-Time markets, along with a Regulation Market exclusively in the Real-Time market (PJM, 2023). In addition to PJM, reserve markets can be found in multiple markets across the U.S. This procurement process serves to maintain grid stability and facilitate the incorporation of RE sources into the grid in a cost-effective manner.

Recommendations

The CBP has been effective in minimizing the Korean electricity market's overall purchasing costs. However, it has difficulty including external costs such as carbon emissions, which presents market barriers for the clean energy transition. A gradual transition to a price-based pool system could take external costs into account and reduce the use of high-emission energy resources. The number free carbon allowances allocated to coal-power plants must also be drastically reduced.

Because the current spot-only market cannot provide sufficient investment incentives for RE systems, introducing a futures market for low-carbon power sources is necessary. This would let low-carbon power sources hedge their investment risks and encourage RE investments.

As illustrated by examples from the United Kingdom, it is important to recognize that flexible resources such as energy storage systems and synchronous condensers will play significant roles in the future RE power system. Allowing those technologies to participate in the day-ahead and spot reserve markets will lead to compensation based on market prices, presenting attractive opportunities for potential investors.

RE generators face revenue uncertainty due to the volatile nature of electricity markets. To promote investment in low-carbon generators, support mechanisms such as the U.K.'s Contract for Difference (CfD) can be implemented to reduce price volatility and guarantee a certain price level for electricity produced by low-carbon generators.

As RE sources become increasingly integrated into power systems, oversupply can occur, leading to a situation where the supply of electricity exceeds the demand. This oversupply can be signaled to market participants through the use of negative pricing. This presents an opportunity for flexible energy suppliers and consumers to take advantage of abundant, affordable energy to lower their costs.

Reserve markets must be established and operated to maintain grid stability and support the integration of RE sources into the grid. These markets should comprise diverse reserve types, such as operating and regulation reserves, that are procured through competitive tendering and market-based mechanisms.

Conclusions and Areas for Further Research

The strategies outlined in this paper include the following key policy recommendations and indicate areas that remain for further analysis of potential strategies to achieve deep decarbonization in the Korean power sector.

First, system reliability standards need to be improved by including system inertia and RoCoF requirements in technical specifications, monitoring systems, and forecasting capabilities. In addition, services capable of supplying grid inertia need to be identified, including real rotating machines and synthetic inertia resources for both the mainland and Jeju Island.

Further research to support potential improvements in system reliability strategies includes:

How can Korea's power system address the system reliability challenges of operating with higher levels of intermittent solar and wind generation, including primary frequency control and voltage stability concerns with decreasing numbers of fossil-fueled generators?

Second, it is necessary to relieve the line congestion anticipated from additional RE generation. This might require large-scale reinforcement and expansion of the transmission system, as well as new approaches such as directly connecting RE production areas to demand areas using subsea HVDC lines. Proactive, early-stage transmission planning and management, rather than reactive measures taken in response to pressing concerns about energy economics (congestion) and reliability (facility age), can help minimize grid connection delays. Further research to support potential resource adequacy planning strategies includes:

- Which entities should be responsible for long-term planning to ensure power systems can meet reliability targets?
- How should wind, solar, and energy storage systems be credited toward resource adequacy?
- How should resource adequacy mechanisms be designed, enforced, and integrated with spot markets?

Third, early participatory stakeholder engagement and informed consensus building can help address and diminish local concerns about RE that might lead to opposition. Integrated resource planning can help alleviate potential land-use conflicts and reduce apprehensions about environmental impact. Further research to support potential integrated resource planning strategies includes:

How can land-use planning ensure efficient and fair access to land for wind and solar developers, while minimizing the impacts of wind and solar development on conservation goals and the agricultural sector?

Fourth, recommendations for promoting emerging RE technologies include designating RE zones to boost market confidence, reduce investor risk, and avoid delays in permitting. Simplifying auction design and making site-specific awards primarily based on price will increase the competitiveness of emerging technologies and reduce investor risk. Further research on potential strategies to support emerging technologies includes:

Offshore Wind

- What technologies, approaches to transmission interconnection, and ownership and business models are most appropriate to Korea's offshore wind industry?
- What mix of policies and markets can help rapidly increase the scale of offshore wind manufacturing and deployment?

Electricity Demand Forecasting

- How can long-term electrical demand forecasts be used in infrastructure planning and policy modeling by sector to account for the impacts of electrification and demand flexibility on load shapes?
- How can uncertainty in electricity demand be best captured in planning and policy studies?

Management of Technological Uncertainty

How can energy policy, regulation, and markets in Korea encourage innovation in new zero-emissions technologies and enable the lowest cost, most effective technologies to rapidly achieve scale?

Fifth, making regulations transparent and creating markets for capacity, flexibility, and ancillary services can make it possible for ESS to compete with other technologies and measures that provide energy system flexibility. Even so, ESS still requires direct support in the form of mandates and regulatory policies. Further research to support potential energy storage policy strategies includes:

- What ownership, business, and operational models are most appropriate for Korea's electricity system?
- What mix of policies and markets can help rapidly increase the scale of ESS?

Sixth, it is important to reform the current, CPB-based market and pricing structures. Market mechanisms to support RE and other clean energy systems need to be considered. Further research to support potential market and pricing structure strategies includes focusing on:

- In the near term, how can the implementation of Korea's cap-and-trade, emissions allowance trading, and renewable quota systems be strengthened?
- In the longer term, how can multiple market systems be harmonized to ensure that they remain effective in supporting national goals and providing consistent incentives?

Lastly, international collaboration will support Korea's transition to a non-fossil-fueled energy system and help overcome technological, economic, and institutional barriers to clean energy deployment.

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Korean Power System Challenges and Opportunities

Priorities for Swift and Successful Clean Energy Deployment at Scale

