Securing Power System Reliability During Renewable Energy Expansion:

In Light of South Korea Power System Operation

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Preface

As renewable energy expansion becomes a core strategy of a country to deal with climate change crisis, countries across the world face challenges of variable renewable energy (VRE) integration to the power system. Korea is also facing a great impact of variable renewable energy on power system operation due to drastic increase of solar based renewable energy.

To address the problems, world's leading countries are taking systematic actions step by step on each of phase of VRE integration. In 2017, IEA classified VRE integration into different phases depending on the level of the share of VRE in the power generation, and identified key challenges in each phase: visibility, flexibility, and reliability. Although Korea is in the early stage of VRE integration, the country's power system is facing all of the challenges simultaneously due to its unique conditions. The Korea's power system is characterized as an isolated power grid with a great portion of nuclear and coal power, and geographical concentration of variable renewable energy in certain areas.

Under the leadership of Mr. Jung Dong-Hee, CEO of Korea Power Exchange, a company-wide task force, KPX Comprehensive Renewable Energy Measures TF, was launched in June 2022. Based on professional experience and knowledge of power system operation in Korea, the task force has drafted a comprehensive master plan of countermeasures to address the VRE integration problems on four aspects of power system (VRE performance requirement, system operation standard, power grid infrastructure, and market system design). The purpose of the master plan is to achieve power grid security while accelerating the expansion of VRE.

This report has been gone through a close scrutiny from external specialists to gain credibility, and reviewed by Kang Taeil, CEO of One Energy Island. We hope this report will contribute to the nations aiming for expansion of carbon-free energy, not to mention Korea itself, and provide further opportunities for discussions and collaborations with other nations on the path of the carbon neutrality.

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Executive Summary

Renewable energy has become the focal point of global efforts towards carbon neutrality. Countries worldwide are actively promoting the deployment of variable renewable energy (VRE), predominantly solar and wind power, in electricity generation as a strategic means to attain carbon neutrality. However, escalating the presence of VRE in electricity generation introduces new challenges to existing power grids. The intermittent nature of VRE generation causes variability in the power system operations, posing difficulties in managing the capacity and technical conditions of the current power systems. To successfully increase VRE in electricity generation and meet carbon neutrality objectives, countries must undergo a profound transformation of their existing power systems to ensure reliable operation.

According to the International Energy Agency (IEA) report titled "Getting Wind and Sun onto the Grid (2017)," the challenges posed by VRE to power systems are categorized into four phases based on the proportion of VRE in electricity generation. The report analyzes major problems encountered by current power systems in each phase and provides recommendations for addressing these challenges. The IEA report emphasizes the importance of 'Visibility' in Phase Two, 'Flexibility' in Phase Three, and 'Reliability' in Phase Four as key themes for VRE integration requirements that the current power systems should address to accommodate the increased share of VRE in electricity generation.

According to IEA, South Korea is currently in the initial phase of integrating VRE into its electricity generation. However, owing to the unique characteristics of its power grid, South Korea is experiencing major problems from Phase Two to Phase Four. It is imperative for the country to tackle issues related to 'Visibility,' 'Flexibility,' and 'Reliability' concurrently in order to overcome these hurdles.

This report has been authored by experts specializing in power system design and operation in South Korea. Drawing on their knowledge and experience, the report conducts a thorough analysis of the impact of VRE on South Korea's power system. It delves into the key challenges faced by the power market and power system operation in the country. The report further provides recommendations for addressing these challenges, focusing on technical requirements, grid codes for VRE, new guidelines for power system operation, infrastructure upgrades, and adjustments to power market design to accommodate VRE as a primary generation source.

While the IEA 2017 report served as a foundational reference for identifying problems and measures related to VRE integration, the issues and recommendations presented in this report stem from an in-depth analysis of the current power system operation in South Korea. These insights are informed by studies on available technologies and field practices adopted to manage variability and uncertainty arising from increased VRE in power system operation.

South Korea's power system, characterized by its isolation from neighboring countries, poses unique challenges for VRE integration. The country's power market remains a publicly managed entity, with the Korea Electric Power Corporation (KEPCO) exclusively handling transmission, distribution, and electricity sales to end users. While this centralized system has effectively provided reliable cost-competitive electricity to end users, the growing presence of renewable energy introduces challenges to system reliability. The escalating variability and the influx of new participants in the power market contribute to a changing landscape, necessitating proactive measures from policymakers, power system operators, and the national electric-power company.

The IEA report covered issues spanning Phase One to Four but offered limited and conceptual measures for addressing 'Flexibility' and 'Reliability' concerns in Phases Three and Four of VRE penetration. In contrast, this report presents detailed and actionable measures to effectively tackle these challenges.

The recommended measures in this report were intended for incorporation into the Long-term Basic Plan for Electricity Demand and Supply of South Korea. However, it is anticipated that the problem analysis and recommended measures in this report will serve as practical guidelines for policymakers or power market authorities facing similar power system conditions to those in South Korea during long-term energy transition planning

CHAPTER ONE.

IEA's Report on Key Challenges of Power Grid with RE

1 IEA's Report on Key Challenges of Power Grid with RE

International Energy Agency (IEA) has categorized the penetration of variable renewable energy (VRE) in electricity generation in four distinct phases, each delineated by an escalating impact of growing VRE capacity on power systems. At each stage, the IEA conducts a comprehensive analysis of the influence of VRE on the power grid, identifying crucial tasks essential for ensuring reliable power system operation. According to the IEA, varying levels of VRE penetration present diverse challenges in the design and operation of power systems.

Phase One

During Phase One, the capacity of VRE has a negligible impact on the system. In a system significantly larger than VRE, encompassing both wind and solar installations, the output and variability of VRE go unnoticed compared to the daily fluctuations in power demand (source: "Getting Wind and Sun onto the Grid," IEA, 2017). The share of VRE in electricity generation at this stage is approximately 3%.

Phase Two

In Phase Two, the impact of VRE becomes more pronounced. Though still manageable through upgrades to operational practices of existing power plants, the IEA suggests that the impact can be addressed. A critical task in this phase is ensuring the "Visibility" of VRE, defined as real-time data on VRE operation for optimal system operator planning.

The primary objective is forecasting the output of VRE to enable flexible operation of conventional power plants, balancing their variability with the demand-side fluctuations influenced by VRE output variations. While there is no specific threshold for entering Phase Two, the IEA proposes a range of 3% to 15%, taking into account different power system conditions.

According to the IEA report, effective power system operation in this stage necessitates adequate information for assessing the current and future state of the system (visibility). Additionally, having the appropriate tools to act on this information (controllability) is crucial. In practical terms, four elements must be in place concerning dispatching operation, with the first two related to visibility and the latter two to controllability.

Table 1: Requirements for Principal power system operation

Visibility	Controllability
○ Visibility of a sufficient number of power plants to the system operator, including VRE. ○ Implementation and use of VRE output forecasts	○ Generation dispatch, management of interconnections with other balancing areas, and management of operating reserves according to load and VRE forecasts ○ Ability for the system operator to control a sufficient number of plants close to and during real-time operations.

Source: International Energy Agency (2017)

As VRE deployment progresses into Phase Two, ensuring the "visibility" of VRE becomes indispensable for maintaining a reliable and cost-effective system operation. This visibility is established through the live (real-time) communication of data detailing the output of VRE, which is then transmitted to the system operator. Choosing an appropriate technology is crucial to guarantee the delivery of accurate and high-quality data to the system operator, forming the foundation for forecasting activities.

Forecasting VRE output, based on real-time data gathered by Supervisory Control and Data Acquisition (SCADA) systems, serves as a fundamental approach for predicting the behavior of VRE. However, to provide a confident representation of net demand, enabling the scheduling of dispatchable and other resources on a day-ahead and several hours before real-time operations, a more comprehensive suite of forecasting tools may be necessary. If the existing SCADA system proves inadequate in delivering quality information or accommodating a sufficient number of measurements, an upgrading may be required.

The management of VRE data can pose challenges due to its large volume, potentially overwhelming a conventional control center. It is important to note that achieving sufficient visibility of VRE does not imply the need to monitor each individual plant in real-time, especially for small-scale solar PV systems where installing real-time data monitoring systems may not be cost-effective. Instead, a forecasting system operating on a representative set of systems, computing, and aggregating real-time output can suffice. The accuracy of the overall forecast improves with a wider pool of VRE power plants contributing data to the system operator. It's worth noting that achieving the same system-wide solar PV penetration with a vast number of very small-scale systems can be more challenging than doing so with a smaller number of larger installations (source: IEA report, 2017).

Phase Three

In Phase Three, conventional power systems encounter significant challenges in integrating VRE. During this stage, ensuring the "Flexibility" becomes critical. In this context, flexibility refers to the power system's capability to respond to uncertainty and variability in the supply-demand balance, within the timescale of minutes to hours (as defined in the IEA report). Traditionally, dispatchable resources and the transmission grid have been the primary measure in conventional power systems to address these challenges. Pumped hydro storage has also contributed to enhancing flexibility. However, with the increasing variability in the power system due to higher VRE penetration, more innovative solutions are necessary, including new storage technologies and large-scale demand-side resources.

According to the IEA, the challenge of VRE integration in this phase is shaped by the interaction of VRE properties, the flexibility of the overall power system, and the policy, market, and regulatory frameworks governing this interaction. The IEA recommends the following as the four pillars to secure power system flexibility: i) upgrading the power grid, ii) ensuring the flexible operation of conventional generation plants, iii) implementing storage systems, and iv) utilizing demand-side resources.

It's important to note that during this phase, VRE penetration ranges from 15% to 25% in annual electricity generation, further emphasizing the need for proactive measures to enhance the flexibility of power systems in the face of increasing VRE integration challenges.

Figure 1: Measures for power system flexibility for balancing VRE variability

Source: IEA report, 2017

Phase Four

In Phase Four, VRE penetration in electricity generation exceeds 25%, posing a threat to the stability of conventional power grids. The stability of a power system, defined as its resilience in the face of events that could disrupt its normal operation on very short timescales, typically a few seconds or less (as per the IEA report), becomes a paramount concern. During this stage, the conventional power system encounters novel challenges, with the primary focus shifting towards ensuring the "Reliability" of the power system.

The challenges and tasks in power system operation across the four phases of VRE penetration, as outlined in the IEA report, are summarized in the following table:

Table 2: Challenges and key tasks on power system operation at each phase of RE penetration

Phase	VRE penetration	Impact on power grid	Tasks
One	< 3%	○ No noticeable impact or localized impact of VRE - Reduced output of conventional generators during very low load period - Localized impact of VRE at their point of connection	○ Assessment of impact of VRE - Proper assessment of the impact of VRE at local grids - Setting grid connection norms of VRE
Two	3~15%	○ Increased variability of power system operation - Decreased accuracy of VRE forecasting due to missed real time data acquisition of RE - Possible transmission congestion at local areas - Disproportionally large reserve capacity requirement against variability	○ Securing Visibility - Introduction of VRE monitoring and forecast system - Adjusting conventional generators to respond to power system variability - Grid codes requirement for VRE
Three	15~25%	○ Significant VRE integration challenge ○ Increased variability and uncertainly of power system operation - Significant changes in power flow patterns across the grid, driven by weather condition at different locations - Increased two-way flows between high and low voltage parts of the grid ○ Constrained power grid capacity to absorb VRE generation	○ Securing Flexibility - Securing flexibility resources to respond to variability - Improving of power system operation and electricity market
Four	25~50%	○ Power grid stability at risk ○ System-wide impact of VRE, and threatened power grid stability - VRE covers nearly 100% of demand at certain times ○ Required grid-wide reinforcement and power system resilience to withstand disturbance	○ Securing Reliability - Sustaining power system inertia and strength - Market design change to accommodate VRE as the primary source of generation

*Beyond the stage 4 (50 % or higher of RE in electricity generation), new measures are required to respond to overgeneration problems. The required measures include various types of storage capacities, and new ITC convergence technologies.

Power system characteristics that determine the extent of integration challenges

Despite the categorized phases of VRE integration challenges, the real conditions of these challenges exhibit variations contingent upon the diverse power system characteristics found in other countries. The timing correlation between VRE output and power demand, the level of smoothing achieved through geographic aggregation, the size of the system, the operator's proficiency in forecasting VRE output, and the structure of the electricity market collectively determine when a new phase of integration is attained (IEA, 2017).

According to the IEA report, the following power system characteristics determine the conditions for VRE integration.

i Geographic and technological spread of VRE

More diverse geographic allocations of VRE deployment and mix of different VRE technologies imply lesser challenges. Geographic and technological diversity provides a 'portfolio effect' and smooth out the variation of VRE outputs.

Also size of VRE matters. Larger systems face lesser challenges. On the contrary, large number of small VRE systems creates more challenging integration problems. Capacity of VRE plays an important factor. Capacity value (the terminology is different from capacity factor) indicates the extent to which VRE can be relied upon like conventional power plants. The capacity value of VRE thus varies from place to place, and with the size of the system considered. The capacity value is further improved by combining both wind and solar technologies, whose outputs may be complementary.

Latitude is also important: at lower latitudes, it is likely that there will be little seasonality either in demand or in solar PV output, meaning less or no necessity of measures to accommodate inter-seasonal variability. In contrast, at higher latitudes there may be a complementary mix of wind and solar output profiles that can help manage seasonal differences. On the contrary, at higher latitudes, the electrification of heating could lead to a peak winter demand several times larger than summer peak, increasing the need for measures to respond to inter-seasonal variability.

ii Corresponding between demand and VRE output (seasonal and daily)

The coincidence of VRE output with peak demand is another major factor. For example, solar PV reaches peak output at the hottest times of the day; if there is a large air-conditioning load then this pattern of output will fit well, and the capacity value of solar megawatts will be higher. Wind energy, being less regular in output, benefits less from this demand complementarity.

iii Scale of Power System

A large power system may accommodate higher VRE penetration than smaller power systems. This is typically the case where sub-regional grids exist, connected to a larger regional grid via interconnections. The bigger the size of a power system, the lower the challenges of VRE integration. A power system connected to neighboring systems has more flexibility to accommodate power system variability caused by VRE. On the contrary, an isolated power system like that of South Korea, face more challenging and accelerated integration problems.

iv Power market structure

Power market structure plays an important role in VRE integration challenges. Real time power market(RTM) offers better a condition for VRE integration.

Beyond Phase Four

Although only four phases of VRE deployment are discussed herein, further VRE deployment beyond Phase Four is possible. According to IEA, in Phase Five, a structural surplus of VRE generation becomes the key issue. If overlooked, these surpluses would result in large-scale curtailment of VRE output, and thus limit further expansion of VRE. At this point, further VRE deployment is likely to require the electrification of other end-use sectors, with heating and transport being promising options.

On the other hand, Phase Six may be characterized by structural energy deficit periods resulting from seasonal imbalances between VRE supply and electricity demand. Bridging occasional multi-day/week shortfalls of supply is likely to stretch beyond the capabilities of demand side response or storage capacities. Storage technologies, Pumped Storage Hydropower (PSH) and Battery Energy Storage System (BESS), which are current available, are sources of flexibility over shorter periods.

Ultimately, if VRE is to dominate a power system, it is likely to be necessary to convert electricity into a chemical form that can be stored cost-effectively at scale, for example in the form of synthetic natural gas or hydrogen.

Grid integration of VRE as a component of a holistic, long-term strategy of green energy transition

Efficient grid integration of VRE will see measures that are appropriate and proportionate to the deployment phase. In some systems these measures can be implemented using existing assets, in others it may be required to invest in additional infrastructure. In both cases, a failure to keep pace with rising VRE share will lead to greater cost in the long run and may threaten the security of the power system. Conversely, putting in place excessively high requirements can also increase costs and/or slow deployment.

According to the IEA, the Four Phases approach should be embedded in wider energy planning, to ensure the smoothest and most cost-effective rollout of VRE. In particular, the report highlighted the measures presented in Phase Two to mitigate adverse impacts of VRE; these center on choosing the right portfolio of VRE technologies (wind/solar), and of strategic allocations of VRE, both geographically (dispersed/concentrated, far from/close to load), as well as in terms of grid voltage (distributed/centralized).

The IEA report also highlighted that VRE integration is itself a subset of wider and longer-term energy strategy that a power system can choose for its long-term energy mix and supply-demand balance. The report recommended a holistic, long-term view of energy strategy to help market participants and system operators to anticipate changes, which will ease VRE integration in a secure and least-costly fashion.

CHAPTER TWO.

Characteristics of Power System in South Korea

2 Characteristics of Power System in South Korea

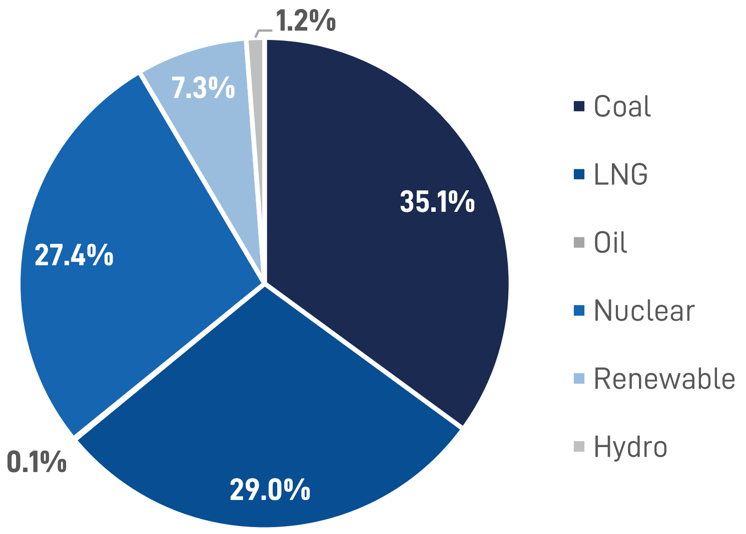
2.1 South Korea's Power System

2.1.1 Overview

South Korea's power system encompasses the mainland, Jeju Island, and an additional 302 populated islands that are interconnected through the national grid. The mainland and Jeju Island are linked by two undersea HVDC cables. Moreover, there are 127 isolated islands that rely on stand-alone microgrids, predominantly powered by diesel generators. With a total population of 51.74 million as of the end of 2021, South Korea ranks as the 7th largest electricity consumer in the world. In terms of per capita electricity consumption, South Korea holds the third position globally, with a consumption rate of 10,330 kWh per person. This places it behind Canada (15,076 kWh) and Sweden (12,451 kWh). The average electricity load in 2021 amounted to 65,846 MW with a peak load reaching 91,141 MW. As per Korea Power Exchange (KPX) data from May 2023, South Korea's total generation capacity stands at 139,048 MW. Coal, nuclear power, and natural gas constitute the three primary sources of power generation, accounting for 38,128 MW (27.4%), 41,201 MW (29.6%), and 24,650 MW (17.7%), respectively. Renewable energy contributes a generation capacity of 28,984 MW, representing 20.8% of the total generation capacity. This includes solar PV with 21,953 MW (15.8%), wind power with 1,931 MW (1.4%), and hydropower with 1,800 MW (1.3%).

Like the mix of the power generation capacity, South Korea's electricity generation mix is still dominated by non-renewable sources, particularly coal, natural gas, and nuclear power, which accounted for 35.1%, 29.0%, and 27.4%, respectively, of the total 577 TWh generated in 2021 (Figure 2). In contrast, renewable energy sources, such as solar PV and wind, contributed only 7.3% of the total generation, with solar PV and wind providing roughly half of that amount. In addition, hydropower produced 1.2% of the total electricity generation.

Figure 2: Share of Electricity Generation in South Korea by Sources (2021)



Source: Korea Energy Agency (2022)

The use of solar PV and wind energy has increased significantly in the past five years, with solar PV generation growing fivefold since 2014. This trend has continued, with solar PV and wind capacity increasing substantially. By May 2023, the installed capacity of solar PV and wind stood at 24,4GW and 2.0GW respectively. In addition, the projects in development path of solar PV and wind are 11.7GW and 20.0GW respectively.

Table 3: The current renewable energy capacity in South Korea [GW]

Category	Solar PV	Wind	Fuel cell	Other*	Total
In operation	24.4 (80%)	2.0 (6%)	0.9(3%)	3.4 (11%)	30.7(100%)
Under-development	11.7 (32%)	20.0 (55%)	3.6(10%)	1.0(3%)	36.6(100%)

*Other renewable includes hydropower

Source: Korea Energy Agency

By the end of 2023, the total installed capacity of renewable energy excluding hydro is expected to reach 32.8GW, accounting for 22.1% of the estimated total generation capacity of 148.6GW. The share of solar PV and wind energy in the electricity supply is expected to exceed 10% by the end of 2023. This marks a significant development in South Korea's power system, which operates as an isolated power system without connections to neighboring countries. Historically, wind power has not played a significant role in South Korea's electricity supply due to limited on-shore wind resources and most of the available on-shore wind resources being in protected areas, such as national parks. However, significant off-shore wind resources have been identified, and currently, large-scale off-shore wind power projects are under development. Off-shore wind and solar PV will lead the increase in renewable energy generation in the future.

2.1.2 The 10th Basic Plan for Long-Term Electricity Supply and Demand

The 10th Basic Plan for Long-Term Electricity Supply and Demand(BPLE) published in 2023 has outlined the country's generation mix plan from 2022 to 2036, with an expected continuous growth in the installed capacity of renewable energy. By 2036, the accumulated installed capacity of renewable energy is expected to reach 108.3GW, more than three times the installed capacity of 32.8GW by the end of 2023. During the period between 2022 and 2036, electricity demand is projected to increase by 1.5% annually. In 2036, peak demand is predicted to reach 118GW, and the total electricity demand is forecasted to be 667.3TWh.

Table 4: South Korea's Power Generation capacity Mix Plan (2022-2036)

Year	Unit	Nuclear	Coal	LNG	Renewable	Other	Total
2023	GW	26.1	40.2	43.5	32.8	5.9	148.4
	(%)	(17.5)	(27.1)	(29.3)	(22.1)	(4.0)	(100)
2030	GW	28.9	31.7	58.6	72,7	6.1	198.0
	(%)	(14.6)	(16.0)	(29.6)	(36.7)	(3.1)	(100)
2036	GW	31.7	27.1	64.6	108.3	7.3	239.0
	(%)	(13.2)	(11.3)	(27.0)	(45.3)	(3.2)	(100)

*Other generation source includes pumped hydro, waste energy, and other ESS

Source: The 10th Basic Plan for Long-Term Electricity Supply and Demand, South Korea

The share of renewable energy in the generation capacity will increase from 32.8GW in 2023 to 72.7GW in 2030, and 108.3GW in 2036. By the end of 2036, renewable energy, mostly solar PV, and wind, is expected to share 45.3% of the total generation capacity of South Korea.

Table 5: South Korea's Renewable Energy Target by 2036 (Installed Capacity)

Year	Unit	Solar PV	Wind	Fuel Cell	Other*	Total
2023	GW	25.2	2.2	1.1	4.3	32.8
	(%)	(76.8)	(6.7)	(3.4)	(13.1)	(100)
2030	GW	46.5	19.3	2.5	4.4	72.7
	(%)	(64.0)	(26.5)	(3.4)	(6.1)	(100)
2036	GW	65.7	34.1	3.9	4.6	108.3
	(%)	(60.7)	(31.5)	(3.6)	(4.2)	(100)

*The other renewable energy source includes hydropower

Source: The 10th Basic Plan for Long-Term Electricity Supply and Demand, South Korea

In terms of the penetration in electricity generation, renewable energy is expected to increase from 7.3% in 2021 to 21.6% in 2030, and 30.6% in 2036. One additional point to be considered in the generation mix plan is the rapid increase of hydrogen and ammonia in electricity generation from nothing to 7.1%, 47.4TWh, in 2036. From 2023 to 2036, the increased share of renewable and hydrogen energy will offset the decreased share of coal and LNG in electricity generation.

Table 6: Estimated amount and mix of Electricity Generation

Year	Unit	Nuclear	Coal	LNG	Renewable	Hydrogen & Ammonia	Other	Total
2021	TWh	158.0	202.7	167.0	41.9	0.0	7.2	576.8
	(%)	(27.4)	(35.1)	(29.0)	(7.3)	(0.0)	(1.3)	(100)
2030	TWh	201.7	122.5	142.4	134.1	13.0	8.1	621.8
	(%)	(32.4)	(19.7)	(22.9)	(21.6)	(2.1)	(1.3)	(100)
2036	TWh	230.7	95.9	62.3	204.4	47.4	26.6	667.3
	(%)	(34.6)	(14.4)	(9.3)	(30.6)	(7.1)	(4.0)	(100)

Source: The 10th Basic Plan for Long-Term Electricity Supply and Demand, South Korea

2.1.3 Power system operation in Jeju

Jeju Island, under the administrative body of Jeju Special Self-Governing Province (JSSGP), is the largest and southernmost island in the South Korea, with a population of 700,000. The island was designated as a World Natural Heritage by UNESCO in 2007. Recognized as the most nature-friendly region in Korea, Jeju is home to a rich natural heritage and attracts over 10 million tourists every year.

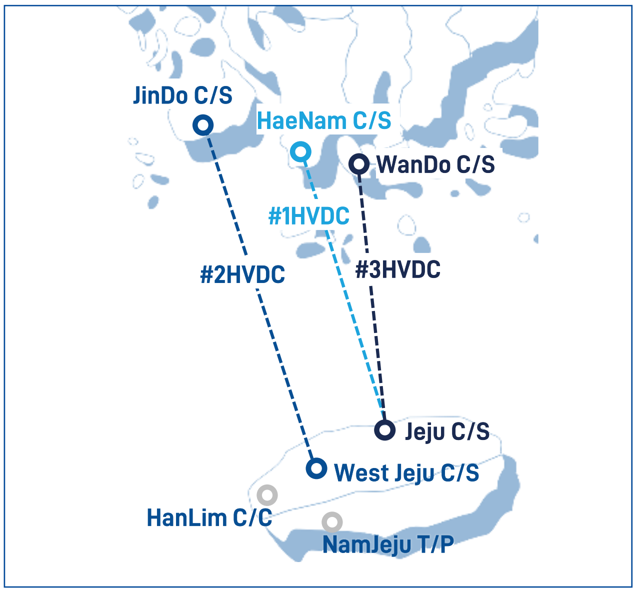
Jeju Island has emerged as a showcase of green energy technologies in South Korea. In 2015, the Korean government announced an initiative titled "Jeju Carbon Free Island 2030," which aims to transform the island into a green industrial powerhouse. The plan focuses on expanding renewable energy generation and energy storage system (ESS) capacity, as well as promoting electric vehicles (EVs), while preserving the island's pristine natural habitats. The initiative was revised in June 2019 to align with the evolving landscape of the global renewable energy market.

Current power system of Jeju: Electricity supply

As of the end of 2022, the total generation capacity of Jeju was 2.213GW. Among this capacity, conventional power plants accounted for 910MW, while renewable energy sources, primarily solar PV, and wind, contributed 903MW. Each of these sources represented approximately 41% of the total generation capacity, respectively. The remaining generation capacity is supplemented by first and second High Voltage Direct Current (HVDC) lines connected to the mainland. Construction of a third HVDC line with a capacity of 200MW is currently underway and is expected to be operational by 2024.

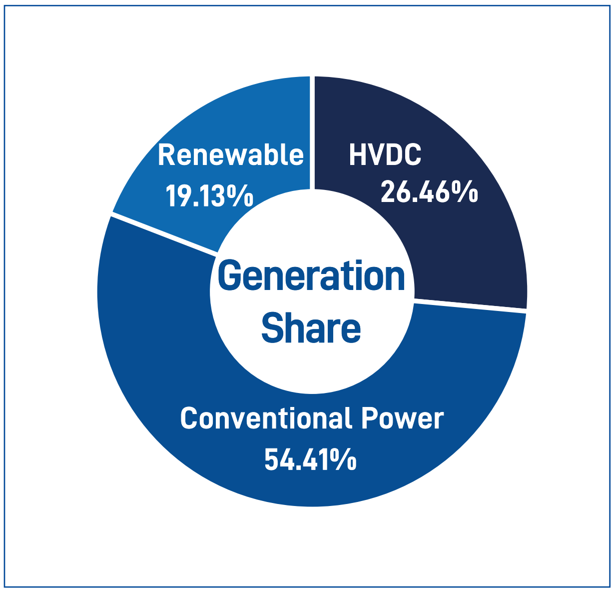
In terms of electricity generation, the conventional power accounted for 55.1% of the share, followed by the #2HVDC lines with a share of 26.6%. Renewable energy sources represented 18.3% of the total generation, with wind contributing 8.8%, solar PV contributing 9.4%, and other renewable sources making up 0.1%.

Figure 3: HVDC lines between Jeju and Korea mainland



Source: KPX Jeju Regional Headquarter

Figure 4: Electricity generation by sources (2022. 12)



Source: Korea Power Exchange, Jeju Regional Headquarter (2022)

2.1.4 Generation Expansion Plan & Prediction of RE Share in Jeju

Plan for Power Generation Capacity Expansion by 2030

As Jeju Island recovers from the impact of COVID19 on its tourism business, the province anticipates a continuous increase in electricity demand, with peak demand projected to reach 1,660 MW by 2036.

Table 7: Electricity Demand and Supply Prediction, Jeju [MW]

Year	Peak Demand	Target Generation Capacity	Committed Capacity Plan	Gap	Capacity Reserve	Targeted Capacity Reserve
2025	1,275	1,632	1,526	▲ 106	19.7%	28%
2030	1,482	1,912	1,594	▲ 318	7.6%	29%
2036	1,656	2,186	1,609	▲ 577	-2.8%	32%

Source: The 10th Basic Plan for Long-Term Electricity Supply and Demand, Jeju, KPX

Table 8: Expected Renewable Energy Generation Capacity in Jeju by 2030 [MW]

Source of Renewable Energy		2020	2021	2022	2025	2030
Renewable Energy	Wind	295	295	295	651	2,345
	Solar	402	507	575	924	1,299
	Fuel Cell	-	-	-	2	104
	Others	9	9	8	404	410
	Sum	706	811	878	1,981	4,158

Source: The 10th Basic Plan for Long-Term Electricity Supply and Demand, Jeju, KPX

Prediction of the Share of Renewable Energy (RE) in Electricity Generation

With the planned generation expansion, the share of renewable energy in electricity supply is predicted to increase to almost 60% by 2030.

Table 9: Share of Renewable Energy in Power Generation [%]

Category	2022	2023	2024	2025	2026	2027	2028	2029	2030
Wind	10.0	10.5	14.1	13.9	18.9	26.3	30.8	35.6	40.3
PV	10.8	11.5	12.1	14.3	16.3	17.4	18.2	18.9	19.6
Total	20.8	22.0	26.2	28.2	35.2	43.7	49.0	54.5	59.9

Source: KPX Jeju Regional Headquarter

2.2 Power Market Operation in South Korea

2.2.1 Energy Environment in South Korea

South Korea is a resource-poor country with 94% of its energy consumption reliant on imported fuels from overseas. Nonetheless, it is the eighth largest energy user in the world (Table 10). This inherent problem of imbalance of energy supply and demand makes the country vulnerable to external changes such as rising oil prices.

Table 10: Energy-Related Ranking in South Korea

Category	Global Rank	Note
TPES	8	282 mil. ton
Oil Import	5	109 mil. ton
Power Consumption	7	544 TWh
CO_2 Emission	7	589 $MTCO_2$

Source: World Energy Balance 2018 (IEA)

In addition, South Korea is one of the countries with the highest energy-intensive industry in the world. The per capita annual energy consumption of South Korea was 4,660 kg of oil in 2011, almost double the world average of 2,418 kg of oil. Compared to the cases in other advanced economies around the world, the energy consumption of industry in South Korea is remarkably high. The industry segment is responsible for 56.6% of the country's total energy consumption, while the OECD average is 37.3%.

Such characteristics of South Korean energy environment shaped the condition of the country's power market and power system. Supplying energy, including electricity, to the industry in reliable and cost competitive ways was the highest priority of the country's energy policy all time.

2.2.2 Characteristics of South Korea's Power Market

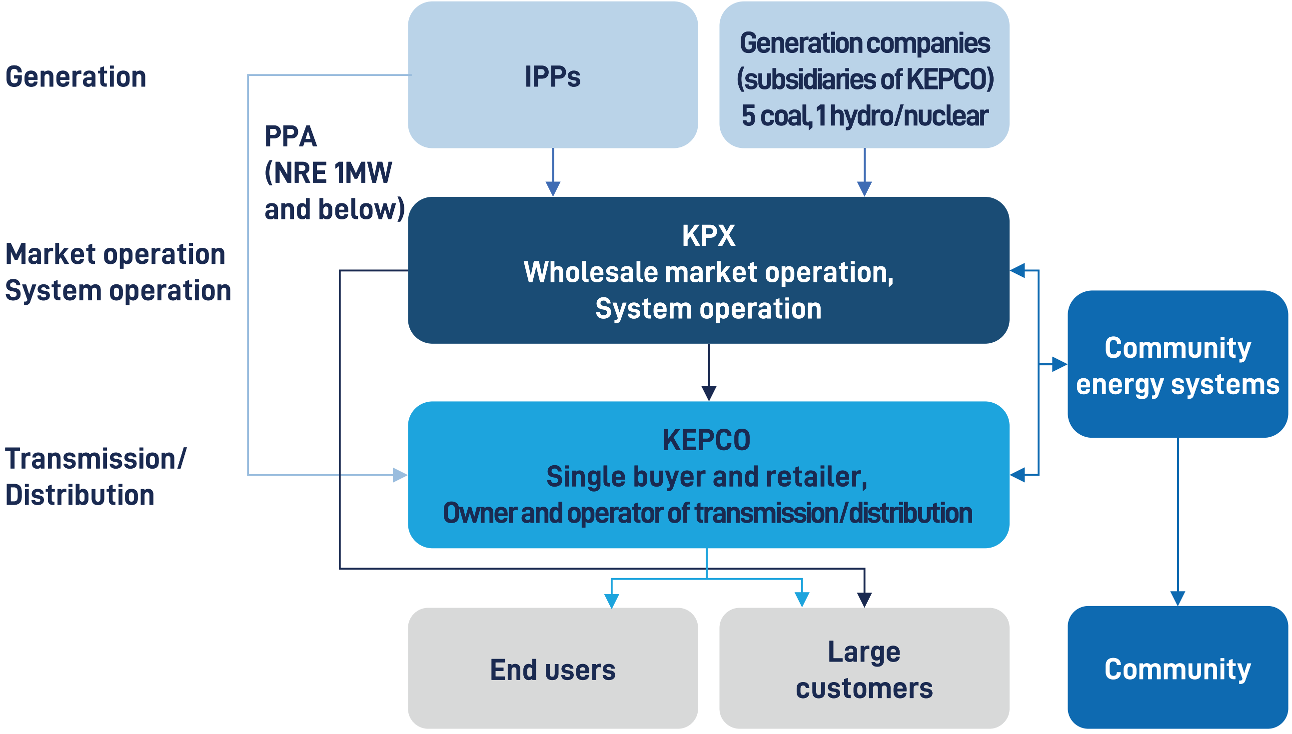
Prior to 2000, Korea Electric Power Corporation (KEPCO) held a complete monopoly over power generation, transmission, distribution, sales, and power market operations in the country. In April 2001, significant changes were implemented. KEPCO underwent a restructuring process, resulting in the division of its operations.

The generation unit of KEPCO was split into six independent business units, comprising five thermal power generation companies and one nuclear and hydropower company. It is important to note that KEPCO still retains a 100% ownership stake in these generation companies. Additionally, the power market operation was separated from KEPCO's purview. To fulfill the role of an independent system operator (ISO), the Korea Power Exchange (KPX) was established.

In 2001, the wholesale electricity market was opened with the participation of ten members, and KPX assumed the responsibility of managing electricity trades within this market. The objective behind these changes was to enhance the efficiency of the power market operations by introducing competition, starting from the generation segment, through the establishment of the wholesale electricity market.

As depicted in Figure 5, the South Korean electricity market continues to be predominantly dominated by the KEPCO and its subsidiaries. KEPCO operates as a regulated monopoly, overseeing the transmission, distribution, and retail of electricity to end-users. It serves as the sole wholesale buyer and retailer in the country, while KPX manages the day-ahead wholesale market.

Figure 5: Korea's Electricity Market Structure



Source: Korea Electricity Security Review, IEA and KEEI, 2021

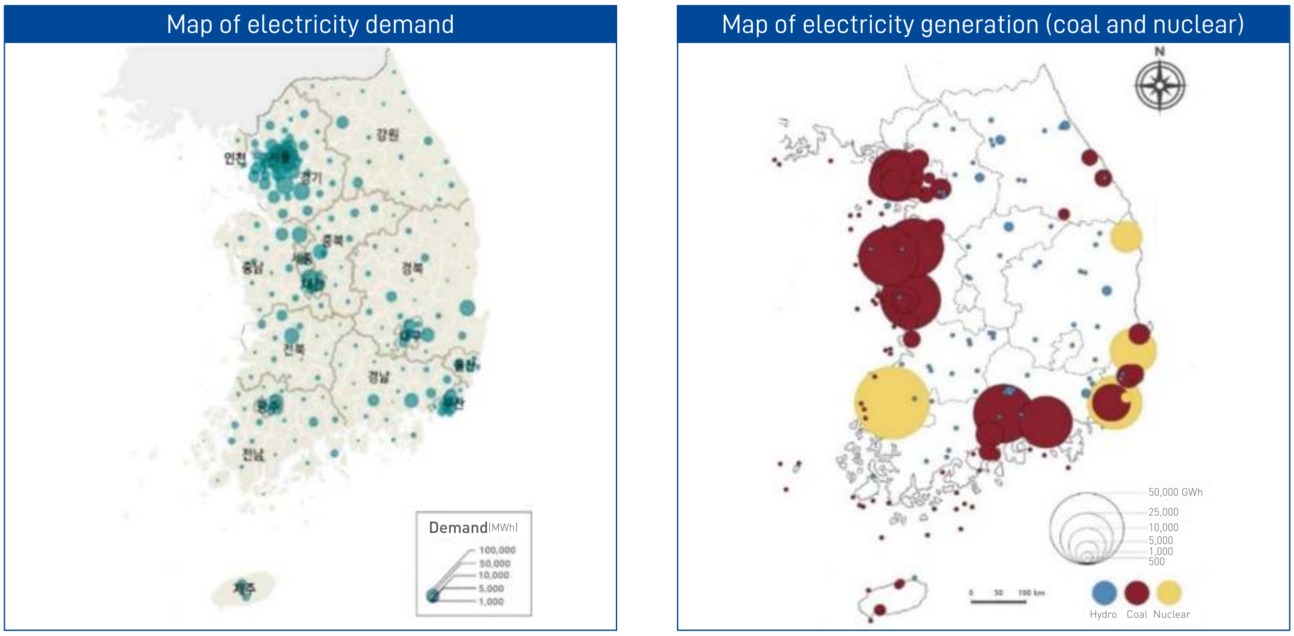
The day-ahead market operates on a cost-based pool (CBP) system, which entails KPX soliciting bids from dispatchable generation resources registered in the pool one day in advance and selecting winners based on their variable costs, with preference given to the lowest bids. The main objective of the CBP operation is to effectively control and manage the costs of electricity within the wholesale market. Participating generation sources in the market are also compensated through capacity payments for their fixed costs.

Six KEPCO's generation subsidiaries and independent power producers (IPPs), including renewable energy producers, sell electricity to KEPCO through wholesale electricity market or by long-term bilateral PPAs (Power Purchase Agreements) exclusively with KEPCO. Still the 6 KEPCO's generation subsidiaries share about 70 percent of the total electricity generation. There is minor exception of this structure. A small number of regional energy business entities provide both heat and power to regional communities directly without the wholesale electricity market or PPAs with KEPCO.

Achieving efficiency in the country's power system has also been pursued through economies of scale. However, the country's dense population and land scarcity, and limited available land for constructing power generation plants and transmission lines created a key challenge in building the country's power system. As a result, the power grid has developed a unique configuration. Sustaining the efficiency of electricity supply by economies of scale of the power generation was the core part of the country's strategy of the power system operation. The large-scale power plants at a Gigawatt capacity along the coast areas where imported coal and uranium is delivered by big ocean carriers, and high voltage transmission lines connecting those power generation units to the capital city or industrial zones has been the landmark feature of the South Korea's power system.

Such geographic characteristics of the South Korea electricity market is a legacy system which South Korea designed and implemented on purpose. The South Korea electricity market has been a highly centralized one under the monopoly of the public utility. The primary goal of the country's energy policy and the national utility has been to supply electricity at the lowest costs in the world to the country's energy intensive industries—steel making, auto manufacturing, chemical, and electronics. The average electricity tariff of South Korea is 60% of the OECD average for residential customers and 83 percent for industrial customers (See the below Figure 7).

Figure 6: Map of electricity demand and generation in Korea

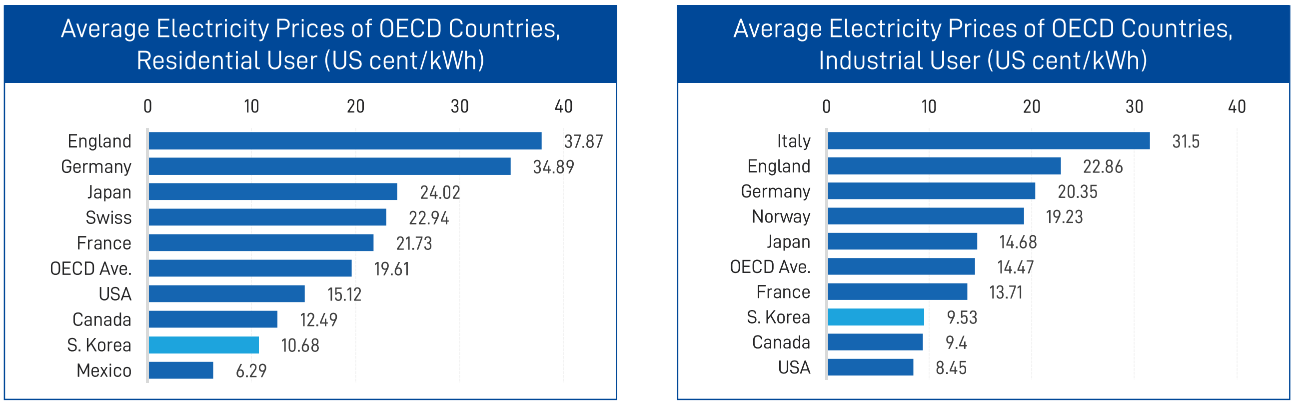

Map of electricity demand

Map of electricity generation (coal and nuclear)

Source: Energy News, Korea (http://www.energy-news.co.kr)

The legacy system also helped South Korea enjoy one of the most reliable electricity supplies in the world. The quality of supply in Korea is also one of the highest across OECD countries, with the system average indicators for the duration (SAIDI) and frequency (SAIFI) of interruptions improving continuously since the 1990s. The power system indicators – SAIFI (system average interruption frequency index, frequency/customer) and SAIDI (system average interruption duration index, minutes/customer) – illustrate how Korea has continuously improved the reliability of its power system. KEPCO has been responsible for managing SAIFI and SAIDI and other indexes representing the level of power quality since 1980 and has strived to improve the reliability of supply. In particular, the deployment of a distribution automation system since 1997 has helped reduce outages significantly through automatic fault location, isolation, and restoration (KEPCO, 2019).

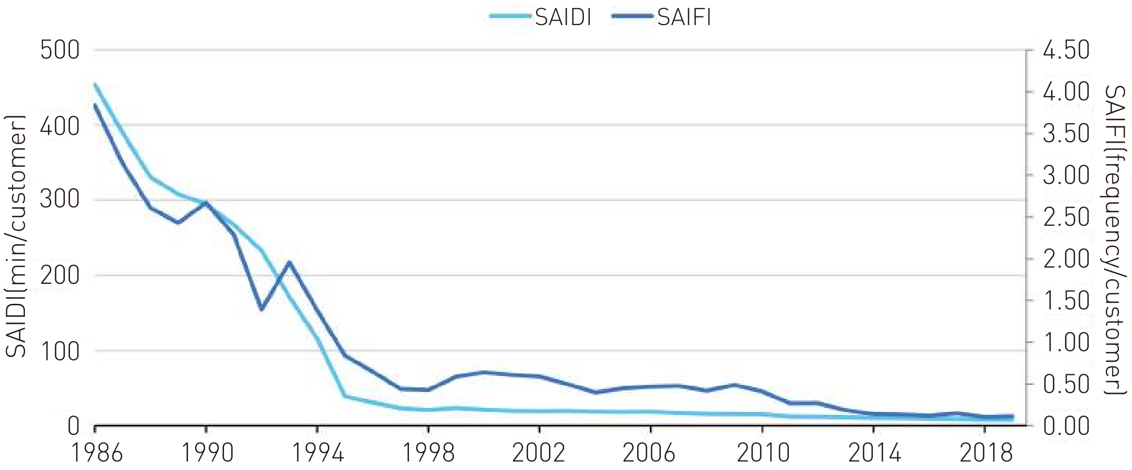
Figure 7: Average Electricity Tariff Comparison Among Major OECD Countries


Average Electricity Prices of OECD Countries, Residential User (US cent/kWh)

Average Electricity Prices of OECD Countries, Industrial User (US cent/kWh)

Source: KEPCO Homepage

Figure 8: Historical trend of SAIFI and SAIDI in Korea, 1987-2019



Source: Korea Electricity Security Review, IEA and KEEI, 2021

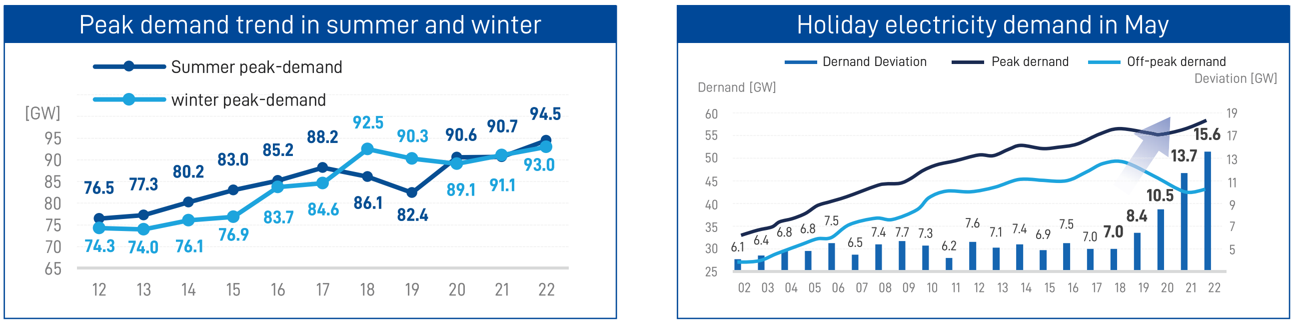
2.2.3 Challenges in Current Power Market during Climate Change Response

Now the South Korean power system faces challenges with energy transition requirement as the country tries to fulfill its carbon reduction goal with increase of renewable energy while sustaining the reliability and efficiency of the power system operation. The challenges come mainly from three directions.

Impact of climate change on the power system operation

The climate change poses significant threats to the power system operation. It requires to reduce traditional power generation sources that produce carbon emission and replace them with variable renewable energy that is not controllable in the existing power grid due to its intermittency. Also, it changes the patterns of energy demand of users. Changing weather with more frequent occurrences of extreme weather changes the electricity demand profile with unexpectedly high demand peaks. For example, in the winter of 2022, severe cold weather caused a record high peak electricity demand in history, reaching 94.5GW at 11am on December 23, 2022. In 2018, on the contrary, severe hot weather caused another record high peak demand, 92.5GW, which exceeded the peak demand target of 87.1GW set in the 8th Basic Plan for Long-Term Electricity Supply and Demand.

Figure 9: Increasing Variability of Electricity Demand in South Korea


Peak demand trend in summer and winter

Holiday electricity demand in May

Source: KEPCO's ESS Operation and Investment Plan, Power System Planning Department, KEPCO, March 31, 2023.

Increased complexity of power system operation

Increasing share of variable renewable energy sources also increases the complexity of the power system operation. In case of South Korea, the power grid in the mainland is in the Phase 2 and Jeju power grid is in the Phase 3. However, due to the specific conditions of its power system, South Korea faces occurrences of visibility, flexibility, and reliability issues at the same time in early stages of renewable energy penetration. In mainland, transmission congestions are observed at local areas where renewable energy plants are aggregated, and power grid shows flexibility and reliability problems during the light load periods in spring and fall months. In Jeju, the number of renewable energy curtailments has been increasing due to over generations.

Table 11: Number of Curtailments in Jeju

Curtailments	'15	'16	'17	'18	'19	'20	'21	~ '22.5
Wind power plants	3	6	14	15	46	77	64	64
Solar PV Plants	-	-	-	-	-	-	1	21

* Curtailment of solar power generation started in 2021 to control overgeneration from solar PV plants

The power grid of the mainland is expected to enter the stage 3 by 2027, and the issues of visibility, flexibility and reliability are expected to become more profound.

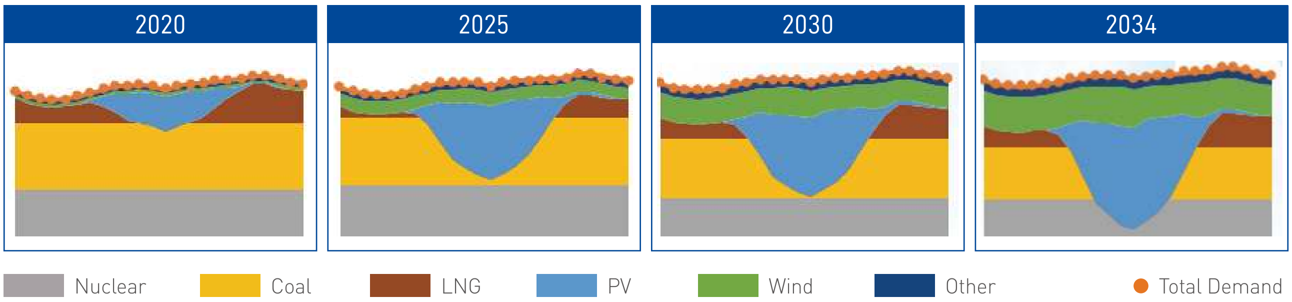
Table 12: Estimated Time of Arrival at RE Penetration Stages

RE penetration stage		Stage 1	Stage 2	Stage 3	Stage 4
Share of RE generation		< 3%	3~15%	15~25%	> 25%
Power grid	Mainland	~ '17	'18 ~ '26	'27 ~ '34	'35 ~
	Jeju	~ '09	'10 ~ '19	'20 ~ '22	'23 ~
Key issues		-	Occurrences and more of visibility, flexibility, reliability issues		

* The arrival times can be shortened in accordance with the national energy policy changes

The replacement of conventional generation plants with VRE sources such as solar and wind, is directly related to the power grid reliability. The increase of solar PV plants results in so called "Duck Curve," which represents net load (load minus RE generation), during the hours between sun rise and sun set, and the power grid faces troubles when the belly of Duck Curve goes below the minimum must-run level of conventional generation units.

Figure 10: Prediction of Average Daily Electricity Generation by Generation Sources



Considering the unique conditions of the power grid of South Korea, it is very important to understand and analyze key challenges and issues to the power grid management. Based on the understanding, a proper roadmap with required measures should be designed in advance for the county to manage the power grid in a reliable way and to support the successful implementation of its Carbon Neutrality Goals.

Changing public view and growing need for decentralization of the power system

The views of public toward the centralized power system are changing. Regional governments, local communities, and individuals who used to be passive consumers of electricity, increase their voices and opinions in construction and operation of power systems. Now they turn to participate as active players in the transition process in the form NGOs or renewable energy IPPs. Growing resents of residents to construction of large power plants or transmission lines in their communities make it more and more difficult to find and secure land for construction of power generation plants to meet growing electricity demand.

All those changes lead to one direction: How to design and manage the power market and power system which will be decentralized with increasing number of stakeholders and complicated with changing patterns in the demand and with a large numbers of distributed energy sources (DES), mostly intermittent solar and wind power in the supply side.

2.2.4 Power System Conditions for VRE Integration in South Korea

In summary, the current power market and power system conditions for VRE integration of South Korea are characterized as the following descriptions.

Isolated grid

First, the power grid of South Korea is isolated without connections with any neighboring power grids. South Korea is surrounded by seas to the east, west and south, and blocked by the Demilitarized Zone (DMZ) to the north. This isolation makes the power system more sensitive and vulnerable to VRE variability than most industrialized countries.

Level of VRE penetration

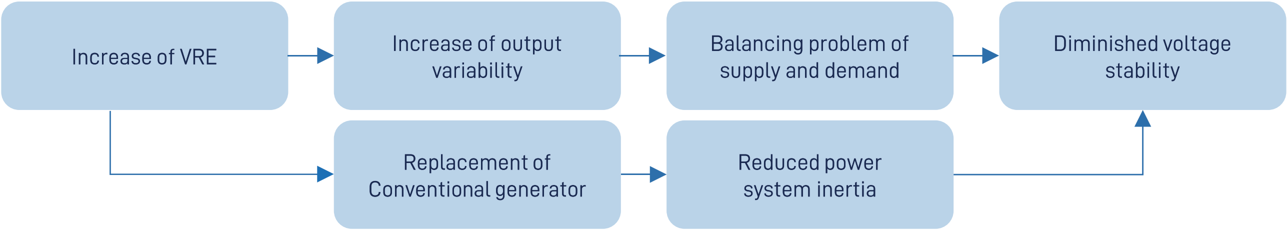
The share of VRE in electricity generation in South Korea is less than 8%. However due to the unique characteristics of its power system, South Korea started experiencing all the problems of VRE integration, Visibility, Flexibility, and Reliability simultaneously. In Jeju Island where the share of VRE is reaching 20%, these problems are more comprehensive and outstanding. Jeju Island is an excellent example of how these Visibility, Flexibility and Reliability issues are presenting and what measures are being considered or taken to address the problems.

Disproportionate concentration of VRE and an imbalanced mix of VRE technologies

The deployment of VRE in South Korea is confronted with unique challenges due to the country's specific physical and geographic characteristics. Solar PV constitutes the majority of VRE capacity, while wind power holds only a minority share. This disparity arises from the restriction of constructing physical infrastructure in areas with high wind power resources, designated as naturally protected areas. Additionally, a disproportionate concentration of solar PV plants is observed in the southern parts of South Korea, located 300 to 400 km away from the densely populated capital and its satellite cities. Most notably, a large number of these solar PV plants are relatively small, with capacities less than 100 kW. It's worth mentioning that these small solar PV systems are excluded from the data collection and management of the system operator.

South Korea is already encountering evolving flexibility requirements, driven by shifts in its electricity generation mix and consumption patterns. As the nation transitions to a greater reliance on variable renewable energy sources, the significance of power system flexibility is on the rise. The escalating share of renewable energy, coupled with the impact of climate change on electricity demand, is anticipated to introduce complexities in power system operation and alter its conditions. On one hand, the proliferation of solar PV and wind energy will heighten the variability of power output, challenging the equilibrium between electricity demand and supply. On the other hand, the replacement of conventional generators by solar PV and wind will diminish the power system's inertia. If left unaddressed, these altered conditions in power system operation may undermine stability in the power system.

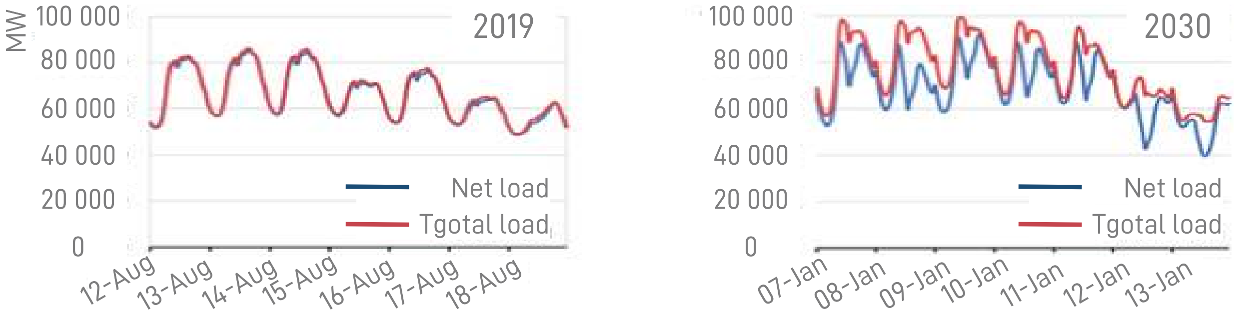
Figure 11: Technical Challenges on the Power System caused by Increased Renewable Energy



Source: BESS Plan and Strategy, KEPCO, 2023

As South Korea continues to accelerate its energy transition, the evolving combination of renewable energy, energy storage systems (ESS), and electric vehicles is anticipated to intensify variability in electricity demand, posing challenges for accurate forecasting. The prediction of net load, calculated as the load minus variable renewable energy generation, is expected to become particularly intricate. The traditional camel curve pattern of the load profile is foreseen to transform into a duck curve, characterized by a substantial decline in net load from sunrise to sunset, with daytime lows potentially dropping below the minimum must-run level of conventional generators.

Figure 12: Prediction of net-load profiles during peak demand periods in Korea (2019-2030)[1]



Source: Korea Electricity Security Review, IEA and KEEI, 2021

In this dynamic scenario, conventional generators are envisioned to operate predominantly during the evening and nighttime periods when renewable energy sources are less active. The figures below illustrate the simulated net-load patterns for South Korea in 2030 in comparison to those of 2019, highlighting the anticipated shifts in the energy landscape.

To address this challenge, Korea must undergo a paradigm shift in its power market operations, incorporating the following measures:

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[1] Note: The load profiles in 2019 and 2030 represent different periods of the year. It should be noted that in 2019 peak demand occurred on 13 August, while the load projection in 2030 has a winter peak according to the assumptions in the 9th BPLE. Source: IEA analysis based on KPX data

Enhancing flexibility in the transmission grid

It is crucial to equip the transmission grid with flexibility resources to effectively manage the variability of renewable energy sources. By implementing advanced technologies and infrastructure, the grid can accommodate fluctuations in supply and demand more efficiently.

Transitioning conventional generators

The role of conventional generators needs to shift from being responsible for base load and peak load coverage to serving as flexible backup sources. This transition will enable greater flexibility in the power system and facilitate the integration of renewable energy.

Revision of the market mechanism

The market mechanism should be restructured to prioritize renewable energy as the primary source of generation, replacing conventional thermal power. This entails allowing renewable energy sources to participate in the wholesale market as dispatchable generation sources, ensuring their active involvement.

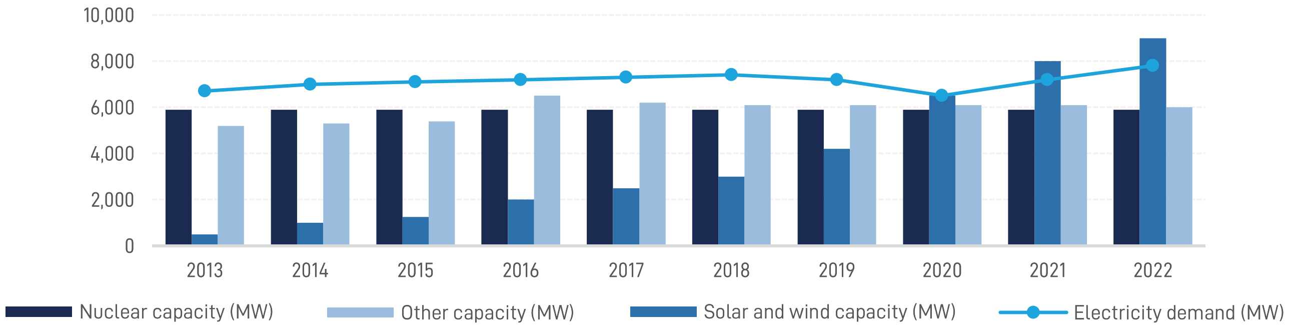
By implementing these strategic changes, Korea can navigate the evolving energy landscape, fostering a more sustainable and resilient power system that harnesses the full potential of renewable energy sources.

2.2.5 RE Integration Problems at Regional Power Systems

While South Korea, on average, is positioned in Phase Two concerning VRE penetration, regional power systems exhibit diverse characteristics in terms of renewable energy integration challenges. As highlighted in the preceding section of this report, a significant concentration of electricity demand is observed in the capital city and neighboring regions, while the majority of generation plants are situated along the coastal areas (refer to Figure 12).

These disparities in electricity supply and demand at regional levels give rise to distinct conditions for RE integration in various power systems. For instance, the Southwest part of the Korean peninsula, spanning two provinces, confronts unique challenges compared to other regions. In this area, the conventional generation capacity, standing at 12 GW, already exceeds the peak demand of 10 GW. The average demand, as of 2022, is 7,491 MW, while the total generation capacity reaches 21,257 GW (2022). This capacity includes nuclear power (5,900 MW), other conventional generation capacity (5,390 MW), solar power (8,843 MW), and wind power (505 MW). Due to the Southeast part of the Korean peninsula experiencing the highest daily solar irradiation in the country, a significant concentration of solar PV plants is evident in this region (refer to the figure below).

Figure 13: Average electricity demand and generation capacity in Southwestern provinces



Source: KPX

The disproportionate supply and demand, coupled with the high concentration of VRE in this region, contribute to power system instability and simultaneous integration challenges spanning from Phase Two to Phase Four. The subsequent tables provide a summary of the significant problems that can manifest in the power system operation within this region.

Table 13: Potential problems in power system operations in the Southwestern power system

Cause of power system instability	Troubles at power system operation
LVRT stop of solar PV plants due to trip of conventional generation plants	Frequency instability by wide-spreading black-out
Troubles at outbound transmission lines	Voltage instability
The rear line fault of nuclear power plants in the regional power system	The transient instability of nuclear power plants in the regional power system
Overgeneration during low demand days	Voltage instability

2.2.6 Power System Operation with Increased VRE in Jeju

The present market operates under the framework of the Cost-Based Pool (CBP), emphasizing the cost of fuel for generation as a key factor. Within the CBP-based day-ahead market, generators employing cost-effective fuels are chosen through bidding processes. Renewable energy sources, characterized by zero fuel costs, are accorded high priority in the power generation selection process.

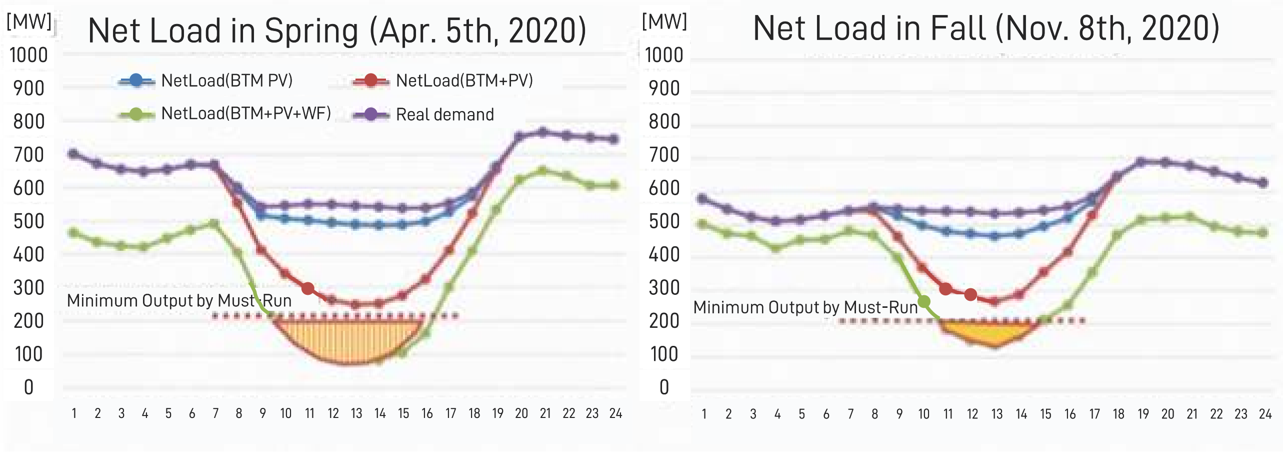
Conventional power plant operation strategy

To ensure operational stability and a reliable power supply, the conventional strategy involves the operation of four thermal generation units. These units serve as the base load generation using bio and heavy oil, while LNG or gas turbines act as flexible generation sources to accommodate the volatility of renewable energy and changing demand.

Renewable energy operation strategy

Renewable energy takes precedence over conventional generators and HVDC in the power system. However, to maintain stability and continuous supply, conventional generators must operate at their minimum levels per load. Currently, KPX reserves 200MW of thermal generators as the must-run capacity. Nevertheless, as the shares of solar PV and wind power increase, there are significant fluctuations in the power demand on Jeju Island, particularly in the net load. During seasons like spring and fall, when the electricity demand is low but solar and wind power generations peaks, the net load falls below the must-run level.

Figure 14: Generation from renewable energy and net-load changes during spring and fall days



Source: KPX Jeju Regional Headquarter

If renewable energy generation increases during periods of low electricity demand, there may be instances of excessive generation. Currently, solar PV has higher priority over wind power, resulting in curtailment of wind power. The table below illustrates the trend and recorded instances of wind power curtailment, along with the corresponding curtailed energy amounts since 2015. The number of curtailments significantly increased, along with the amount of wind power targeted for curtailment. As of 2022, approximately 26 GWh of wind power has been curtailed in total, accounting for 4.26% of the total wind power generation in Jeju.

Table 14: Status of excessive generation and curtailments

Year	Volume of Curtailment (MWh)	Number of Curtailment (Days)	Share of Generation
2015	152	3	0.04%
2016	252	6	0.05%
2017	1,300	14	0.24%
2018	1,366	15	0.25%
2019	9,223	46	1.65%
2020	19,449	77	3.24%
2021	12,016	64	2.18%
2022	25,634	104	4.26%

Source: KPX Jeju Regional Headquarter

2.3 Strategy and Debate over Climate Change Action

2.3.1 Green Growth as the Strategy of South Korea to Respond to Climate Change

In 2009, the South Korean government announced, "Smart Grid National Roadmap," and the 1st and 2nd Intelligent Power Grid Master Plans in 2012 and 2018, respectively. The Smart Grid National Roadmap set critical milestones for the nation's power grid transition from 2010 to 2030, while the subsequent Intelligent Power Grid Master Plans drafted detailed action items to achieve the milestones. The 1st Intelligent Power Grid Master Plan put its focus on R&D and commercialization of key smart grid technologies through implementing testbed projects. The 2nd Intelligent Power Grid Master Plan focused on the creation of new business models in the energy industry.

Those policy programs aimed at the development of a nationwide smart grid. The underlying intention and background to the initiative were to utilize advanced Information and Communication Technology (ICT) to transform the power grid to one that decouples from fossil fuels and reduces carbon emissions while achieving the optimized energy efficiency of both supply and demand. The transition process involved the development new energy technologies in convergence with ICTs, but the eventual goal of the initiative was to create a market for innovative business models and ventures with spun-off technologies from the transition process and thereby find and nurture a new growth engine for the country in the preparation for the Fourth Industrial Revolution era.

There are three driving factors to carry forward with the smart grid in South Korea. The first is to respond to climate change, the second to enhance energy efficiency, and the third to create a new growth engine.

To respond to climate change

Through Intended Nationally Determined Contributions (NDCs), the Korean government set the goal to reduce greenhouse gas (GHG) emissions by 37% compared to the business as usual (BAU) baseline by 2030. To achieve the GHG reduction target, South Korea must establish a low carbon energy infrastructure. Promoting the use of renewable energy and electric vehicles to reduces carbon emissions is not feasible with the conventional power grid. Therefore, it is imperative for South Korea to transit to smart energy infrastructure in order to achieve the NDCs target.

To enhance energy efficiency

Energy efficiency plays a crucial role in reducing carbon emissions. Energy efficiency has been the highest priority in energy policy in South Korea. With its strong ICT foundation, South Korea has very favorable condition to promote efficient use of energy through real-time monitoring and control of power demand and various consumer-centered power services.

To create a new growth engine

South Korea needs to foster the smart grid industry as a new growth engine that surpasses the semiconductors and IT industry, which are the current growth engines of the country. The smart grid is expected to have a great ripple effect in the economy not only in the power and heavy electric industries but also in related industries of communication, home appliances, construction, and transportation. The smart grid is anticipated to contribute to creating new business models and high-quality jobs for the country.

2.3.2 Debates on Energy Transition

While there is a consensus on the necessity of transitioning to green energy for sustained economic growth and to meet NDCs, debates persist regarding the optimal pace and framework of this transition. Players in the traditional energy industry, including public utilities and generation companies, approach the integration of variable renewable energy sources into the power system with caution, emphasizing a gradual approach. On the other hand, proactive groups such as NGOs and local communities advocate for an accelerated shift towards renewable energy and a decentralized market structure. Moreover, external factors also exert pressure on the speed of change. For instance, RE100, a global initiative spearheaded by the EU, mandates that all manufacturing supply chain activities utilize renewable energy, thereby posing a significant threat to South Korea's energy-intensive manufacturing industries. Behind the debates lies potentially conflicting stakeholder interests. Energy transition involves fundamental changes to energy market and energy infrastructure as well as changed roles of players in the market. The transition offers a new opportunity for future growth of a society, but at the same time, it requires changed role of traditional public utilities. Therefore, transition process requires consensus building among stakeholders of a society. Careful management of transition process is very important for the successful energy transition, and mismanagement of transition process can result in delayed and costly energy transition.

CHAPTER THREE.

Key Tasks of VRE Integration to Power System

3 Key Tasks of VRE Integration to Power System

3.1 Grid Code of VRE

Highlights

- Insufficient monitoring (only 25% of VRE accessible) ▶ Lower visibility
- Uncontrollable VRE generation (appx. 5GW variable) ▶ Power balancing risks
- Inadequate technical norms of VRE ▶ Lower power grid reliability

3.1.1 Lower visibility due to insufficient VRE monitoring

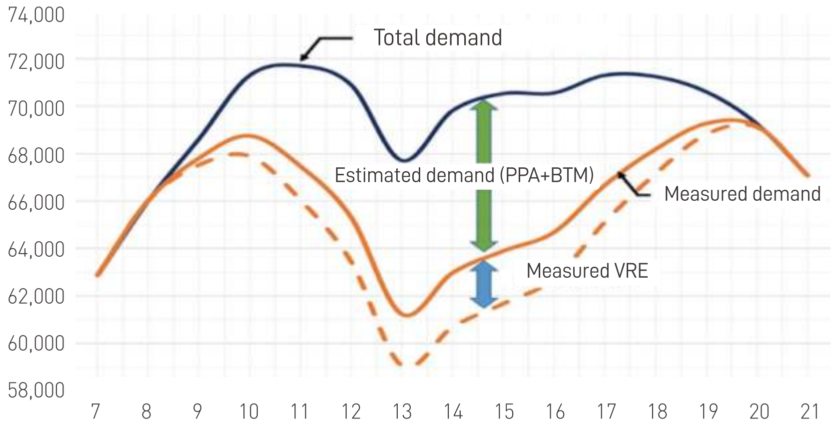
In South Korea, only 25% of renewable energy plants permit data acquisition by the system operator. This implies that real-time operational data is available for just a quarter of the total renewable energy generation. Additionally, within this subset, only 7.5% of the plants provide real-time data (within a 5-minute timeframe), while the remaining 17.5% exhibit a one-hour delay in data availability. For the remaining 75% of renewable energy plants, where real-time data acquisition is not feasible, a statistical approach is employed to extrapolate missing data. To achieve a statistical confidence level of 95%, the sampling ratio needs to exceed 60%.

Table 15: VRE data management, South Korea (End of 2021)

Category	Measured demand (VRE captured in power market)	Estimated demand (VRE of PPA+BTM*)
Capacity (GW)	5.9 (25%)	16.5 (75%)
VRE data acquisition	Possible	No possible
Managed data	Generation	Demand

*PPA (direct contract with KEPCO), BTM (self-consumption)

Figure 15: VRE data management, South Korea (End of 2021)



Inadequate real-time monitoring and data acquisition of VRE diminish the visibility of power system operation and compromise the balance between supply and demand. Consequently, the disparity between the anticipated electricity demand and the actual measured demand widens, leading to a reduction in reserve capacity. In the event of an extreme weather change, a one-unit change in VRE generation triggers a threefold increase in demand, a threefold reduction in supply, and a fourfold decrease in reserve capacity relative to the altered quantity of VRE generation.

Table 16: Changes in supply and demand due to weather change

Weather change	Measured solar power generation (captured in power market)	Demand	Supply	Reserve capacity
Clear ▶ Cloudy	Reduced (-a*)	Increased (3a)	Reduced(-a)	Reduced(-4a)

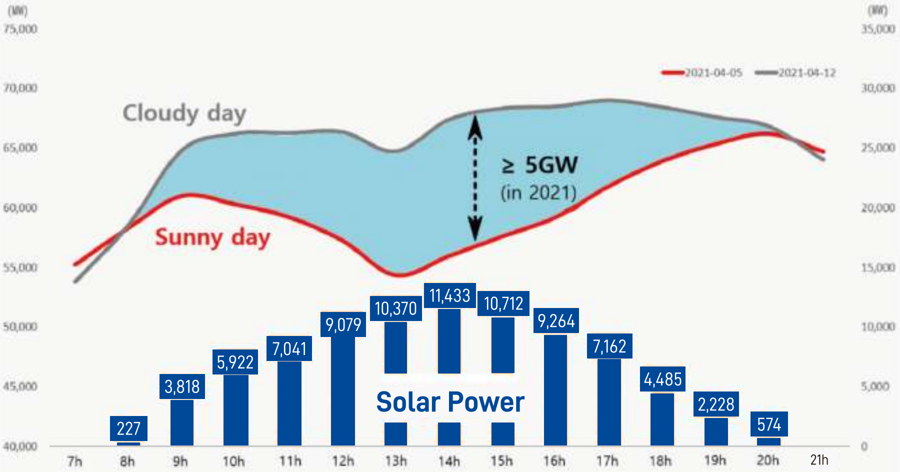
*a: size of variability due to weather change [MW]

The inadequate data acquisition of VRE distorts supply statistics, and inaccuracies in these statistics may hinder the effective planning of VRE deployment in the country. This, in turn, poses a challenge to the successful implementation of the country's 2030 NDC goals.

3.1.2 Weakening supply management due to uncontrollable VRE generation

In 2021, the variability of solar power generation caused by weather changes reached 5GW. The variability is expected to increase to higher than 10GW in 2030 (based on the 9th BPLE of South Korea). Such variability of VRE generation causes significant reduction of reserve capacity. As shown in the following table, during the summer season, the variation of the reserve capacity increased from 2.5GW in 2018, to 3.2GW in 2019, 4.0GW in 2020, and to 5.6GW in 2021.

Figure 16: Fluctuating Power demand in different weather condition



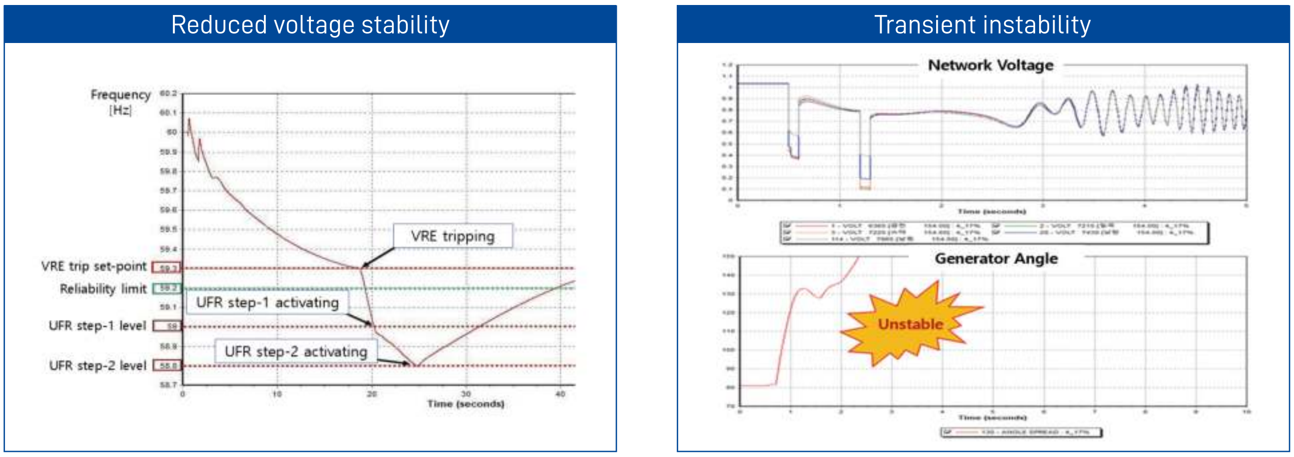
As VRE experiences rapid growth, the availability of conventional generation units, such as coal and LNG, faces constraints. The escalating share of VRE in the generation mix diminishes the role of conventional generation units, and the operational characteristics of these conventional plants prove less adaptable to the inherent variability of VRE. In the southwestern part of South Korea, where 40% of the total VRE are installed, high VRE generation levels induce transmission congestions, and the conventional generators in the region lack the flexibility required to mitigate these congestions.

Managing a power system with VRE as the primary generation source necessitates inevitable control over VRE output. While PSH and BESS can serve as flexibility resources to mitigate VRE variability, the lead time and investment required to establish storage infrastructure mean that these technologies alone cannot adequately address the variability issue. Consequently, additional measures to control VRE generation become imperative. Notably, in Germany, it was reported that curtailing VRE output by 3% of the total VRE generation can lead to substantial savings, including a 40% reduction in investment for transmission line expansion and a 15% reduction in investment for flexible backup facilities.

3.1.3 Power system reliability risks due to the outdated technical requirements of VRE

A significant number of RE plants currently operational in South Korea lack the Fault Ride Through (FRT) function. This absence poses a risk of widespread disruption to RE plants in the event of a trip in conventional generation units or a fault in the transmission system. When the trip of a conventional generation plant leads to a drop in frequency, the protection system in VRE inverters is activated, causing the cessation of VRE generation. An illustrative example of this scenario occurred with the trip of the Shinboryeong thermal power plant in March 2020, which, in turn, triggered subsequent trips in 450MW solar PV plants. This subsequent trip of solar PV plants exacerbated voltage drops and contributed to the destabilization of the power system. Such a chain of reactions has the potential to lead to a widespread blackout.

Figure 17: Power system instability caused by wide-spreading outage of VRE


Reduced voltage stability

Transient instability

*Generation plant trip ▸ frequency drop ▸ spilled over trips of solar power plants ▸ accelerated frequency drops ▸ UFR activated

*Transmission line troubles ▸ voltage drop ▸ RE trips ▸ excessive instability of neighboring generation plants ▸ wide spreading trips of generation plants ▸ accelerated voltage drop ▸ UFR activated

Specifically, the consequences of VRE trips can be exceptionally severe in Jeju, where the power grid is both small and isolated. For example, a transmission line issue in the southwestern part of the island led to the trips of 145MW VRE, constituting 64% of the total 227MW VRE connected to the transmission lines. In the event of a three-phase short-circuit fault, if 400 VRE units are halted due to low voltage, there arises a concern about the operation of 1 to 2 Under-Frequency Relay (UFR).

Countermeasures to Improve performance of VRE

- Secure visibility by real-time monitoring and data acquisition of VRE
- Improve supply and demand balancing by enhanced output control of RE plants
- Secure power system reliability by regulating grid codes for VRE, including FRT function

3.2 Power System Operation

Highlights

- Increase of RE forecasting errors (error rate 8%) ▶ Supply and demand imbalance
- Reduced power system flexibility ▶ Insufficient reserve
- Increase of inverter-based systems (fast response) ▶ Less accurate system analysis
- VRE overgeneration issues in Jeju ▶ VRE curtailments increase

3.2.1 Supply and demand balancing problem due to increasing VRE forecasting errors

Increase of RE capacity results in forecasting errors of VRE generation. Currently the error rate is 8% but the prediction errors is expected to go up as more VRE will be installed.

Table 17: Estimated error rate of VRE generation

Category/ Year	2022	2025	2030
Installed solar PV capacity (Expected, 10th BDSBP)	22.1GW	31.3GW (▼ 0.1GW)	46.5GW (▲ 6.5GW)
Estimated size of solar power forecasting error (Based on 8% error margin)	1.77GW	2.5GW (▼ 0.02GW)	3.72GW (▲ 0.51GW)

* Forecasting error of solar PV generation (Average error margin rate in peak demand summer and winter hours, 2021) (11 am winter 7.65%, 3pm summer 8.42%)

Irrespective of the magnitude of the concerned forecasting errors in VRE generation, there are limited opportunities to enhance the current situation. In South Korea, government incentives favoring smaller solar PV plants have led to a proliferation of plants with capacities less than 100kW, resulting in a substantial increase in their number. From January 2021 to March 2022, 3.5GW (81.3%) of the total installed capacity of 4.3GW for solar PV plants fell within the less than 100kW size category. Monitoring these numerous small solar PV plants proves challenging as owners are not obligated to report to the system operator.

Table 18: Weighted Renewable Energy Credit to Solar PV Plant

Site type	<100kW	100kW~3,000kW	>3,000kW
Ground-mounted	1.2	1.0	0.8
Floating solar	1.6	1.4	1.2

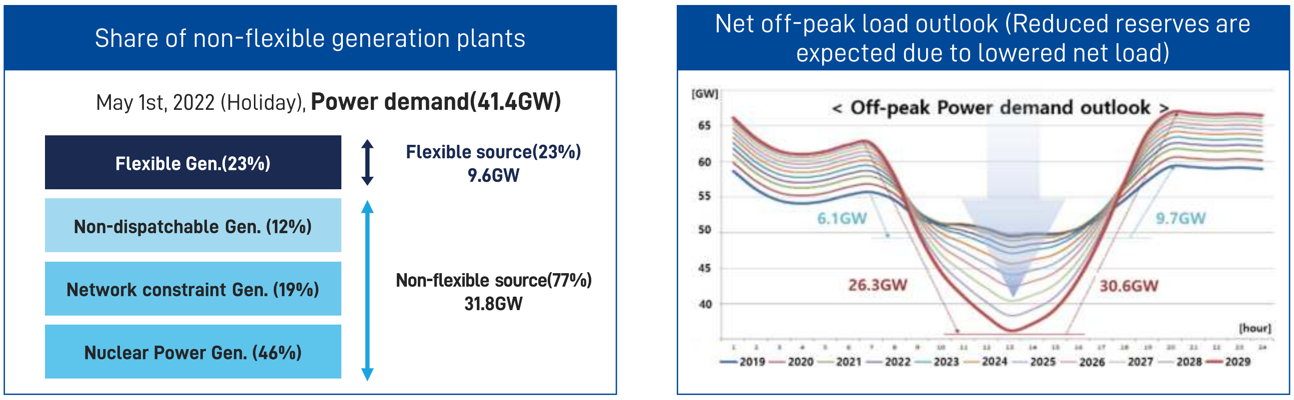
Table 19: Favored Regulations for small Solar PV plants

Exemption of plant requirement	Interconnection terminal	Real-time reporting	Control communication
Exemption of performance requirement	Grid codes	Output monitor requirement	Output control requirement

3.2.2 Reserve capacity decrease due to low flexibility of the power system

The current generation mix in South Korea exhibits a disproportionately high share of non-flexible generation units, encompassing nuclear power plants, VRE, and constrained generators. On a day with a light load, such as May 1st, 2022, the non-flexible generation plants accounted for 77% of the total generation capacity. The prevalence of non-flexible generation units in the power system contributes to a shortage of supply reserves.

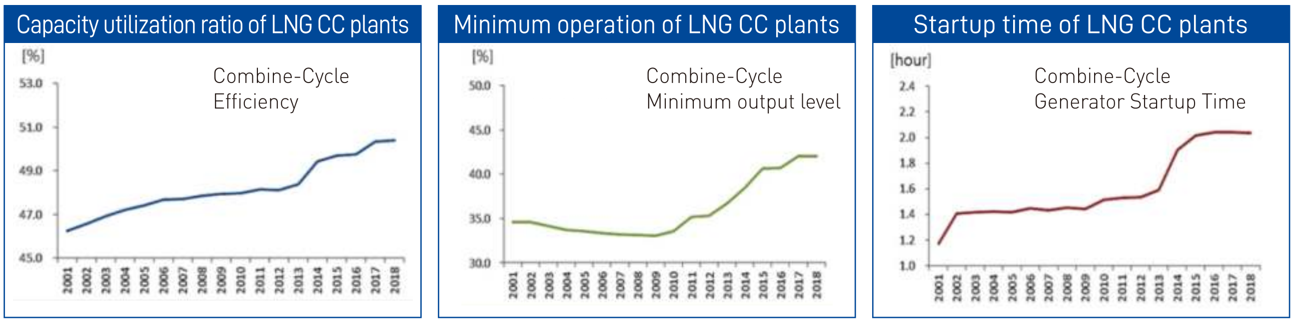
Figure 18: Non-flexible generation and Net off-peak load outlook



* Capacity of non-flexible generation plants (Apr. 2022): 56.3GW, 42% (nuclear 17%, RE 18%, Combined Cycle 7%),
* Expected share of electricity generation from non-flexible generation sources: 59% (2019) ▸ 85% (2024)

Furthermore, the flexibility of thermal generation sources, specifically coal and LNG, is diminishing. Presently, the minimum must-run level for these plants is set at 60%. Under normal conditions, the average output level of thermal generation plants is maintained at 80%, leaving only a 20% flexibility margin between the must-run level and normal operation. Additionally, out of a total of 89 thermal generation plants, only 37 units are capable of independent operation, further constraining the capacity of supply reserves. South Korea's current generation mix strategy emphasizes the expansion of supply capacity and efficient operation of generation plants; however, this approach may not be inherently effective in securing power system flexibility. Consequently, the power system in South Korea grapples with challenges related to a high minimum generating output, extended start-up times, and diminished capacity for independent operation of gas turbines.

Figure 19: South Korean challenges to power system



The supply reserve capacity decrease resulted from the power grid rigidity is shown in the following table. In 2021, there were shortage in the primary reserve capacity for 32 hours, and the secondary supply reserve shortage for 2 hours (The total reserve requirement, 4.5GW, was fulfilled without shortage).

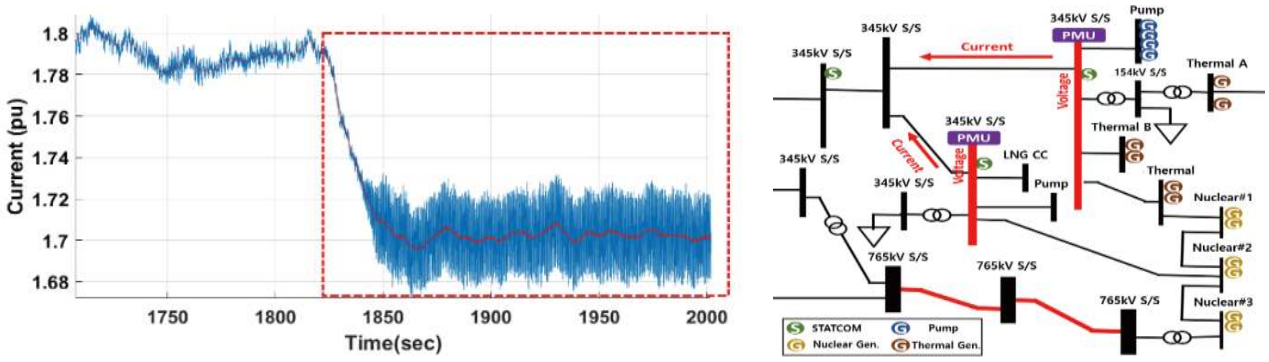
Table 20: Change to reserve status due to increased power system rigidity

Reserve type	Reserve capacity requirement	Unmet reserve capacity (hours)		
		Public holidays (Fri. and Sat.)	Sunday	Total
Primary reserve	>1.0GW	12	20	32
Secondary reserve	>1.4GW	-	2	2

3.2.3 Blind area due to using RMS based power system analysis tools due to increasing number of Inverter-based system

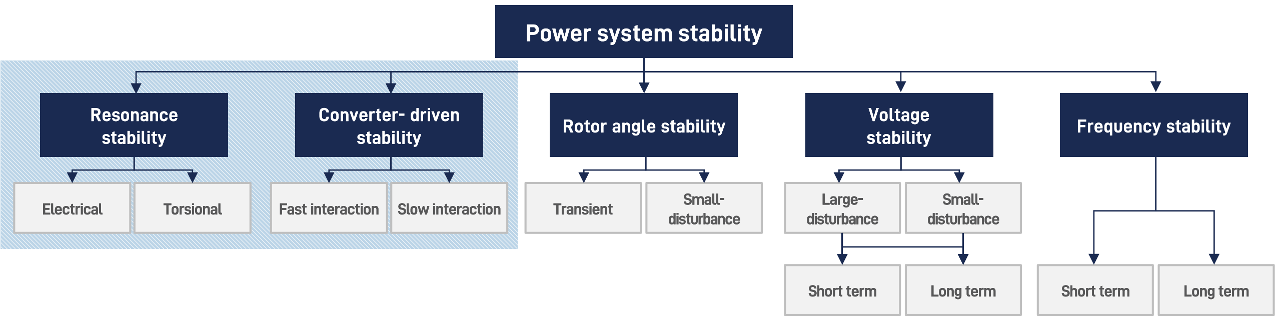
Another factor contributing to power system instability is the evolving dynamics resulting from the increased deployment of inverter systems. With a rising number of inverters in solar PV, wind, HVDC, STATCOM, SVC, and TCSC, the power system encounters new technical barriers, including power system resonance, interactions between inverter-based systems, and oscillations of inverters. These incidents were unprecedented until recent years. For instance, on November 23, 2023, a 2.08Hz vibration was observed twice on a 345kV transmission main line in the eastern part of South Korea's power grid.

Figure 20: TCSC Related Power System Oscillation in Eastern Section of South Korea



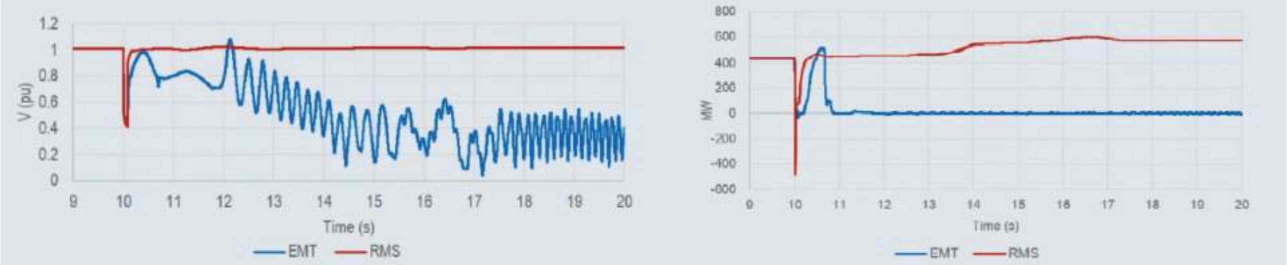
IEEE Std (2018) stipulated new safety regulation regarding inverter systems to address power system instability that can be caused by increasing number of inverter systems. The safety regulation included two category of new stability standards, i) converter-driven stability and ii) resonance stability.

Figure 21: Requirements for power system stability



The conventional approach to power system analysis lacks the capability to perform an electromagnetic power grid analysis based on inverters. The RMS method, relying on the '*ms*' unit in traditional analysis, has limitations when conducting EMT analysis, which is based on the '*us*' unit. The following figures illustrate how two distinct power system analysis methods yielded different outcomes for the same power system incident. In a HVDC trip incident in Australia, the RMS analysis suggested that the power grid remained safe, but technical issues were confirmed when the power system was analyzed using the EMT method.

Figure 22: Case of Different Results between RMS and EMT Analysis



3.2.4 RE curtailment increase due to VRE overgeneration in Jeju

In Jeju, the rapid increase of VRE resulted in overgeneration problem. In 2021, the installed capacity of RE was 829MW, about 40% of the total installed capacity of 2.2GW (The total installed capacity includes two HVDC lines, 200MW each, linked to the mainland). The VRE capacity already exceeded the average load, 670MW, of the island. During the recent two years, the solar PV plants increased two folds from 294MW to 526MW.

Table 21: Increased VRE generation in Jeju

(MW)	Average Demand	HVDC	Conventional generation plants	RE			
				Solar	Wind	Other	RE Total
2019	653	400	798	294	290	8	592
2020	646		929	420	295	9	723
2021	670		929	526	295	9	829

* Minimum demand (MW) of Jeju: 451('19) ▸ 446('20) ▸ 378('21) ▸ 396('22)

Accordingly, VRE curtailments increase. Curtailment orders were initially placed on wind power plants, but from 2021, solar PV plants have been given curtailment orders from the system operator.

Table 22: Increased VRE curtailments in Jeju

Curtailment (days)	'15	'16	'17	'18	'19	'20	'21	~ '22.5
Wind	3	6	14	15	46	77	64	64
Solar PV	-	-	-	-	-	-	1	21

* From April 2022, surplus power trade with the mainland through the HDVC lines was stopped due to the concern of black out, and since then curtailment orders began to be placed on solar PV plants.

In Jeju, for the time being, the installation of new solar PV plants is expected to keep growing thanks to the rising SMP (System Marginal Price) and RPS (Renewable Portfolio Standard) mandate to conventional generation companies. The growing number of solar PV plants will inevitably result in more output curtailments.

Countermeasures to Address Power System Variability

- Improve VRE forecasting with an ICT platform that utilizes AI and big-data technology
- Enforce grid codes and technical requirements for VRE
- Participate in load following service of nuclear power plants with more flexible operation
- Improve flexibility of thermal power plants to respond to supply and demand balancing
- Adopt an advanced power system analysis modeling for increasing number of inverter systems: Power system analysis using EMT model
- Design the power system operation to mitigate VRE curtailments in Jeju

3.3 Electricity Market

Highlights

Low market participation of VRE (VRE participation rate 4.5%)	▶	Lack of VRE capability to respond to supply and demand balancing
Low utilization of demand-side resource (capacity of reliability DR 4.9GW)	▶	Lack of power system capacity to respond to supply and demand balancing
Lack of incentives for flexibility resources (Share of payment for ancillary services of the total electricity market transaction: 0.08%)	▶	Insufficient reserve capacity to respond to supply and demand balancing

3.3.1 Lack of power system resources to respond to supply and demand balancing due to low market participation of RE

KPX introduced "Renewable Energy Forecasting Service Program". VRE generators, as a service provider, receive payments for generation in SMP (System Marginal Price) and REC (Renewable Energy Credit) amount.

According to the program, VRE participating in the wholesale electricity market receive additional payment for participation in the programs based on the forecasting error margins. VRE projects that participate in the electricity market is required to submit predicted generation (The wholesale electricity market in South Korea is a Day-1 market). VRE participating in the market is paid for an additional settlement fee based on the prediction error margins in the following schedule.

3 Korean won per kWh if the prediction error is 6~8%	4 Korean won per kWh if the prediction error is smaller than 6%.

However, the incentive is not big enough, and administrative and regulatory process are too cumbersome to induce participation of VRE in the electricity market. Only 4.5% of VRE are participating in the market. It is necessary to facilitate the participation of VRE sources in the electricity market by improving the regulatory process and financial incentives.

Table 23: VRE Forecasting Program

	Individual Plant	Grouped Plant	Aggregated Plant
Permitted capacity for the program entry	Solar and wind: >20MW	Solar: >20MW Bio: >20MW	○ Eligible generation technology: solar PV, bio, ESS, or small hydro ○ The capacity of each generation source is less than 1MW ○ The aggregated capacity must exceed 20MW

Table 24: Status of VRE Participation in the Wholesale Electricity Market

RE participation in the Market (May 2022)	(a) Electricity market			(b) PPA with KEPCO			(a+b) (MW)
	Wind and solar PV	Other sources	Total	Wind and solar PV	Other sources	Total	
Installed capacity of VRE	8,002	3,848	11,850	13,273	25	13,298	25,148
Capacity of VRE in the participating in the market	1,120	-	1,120 (9.5%)	-	-	-	1,120 (4.5%)

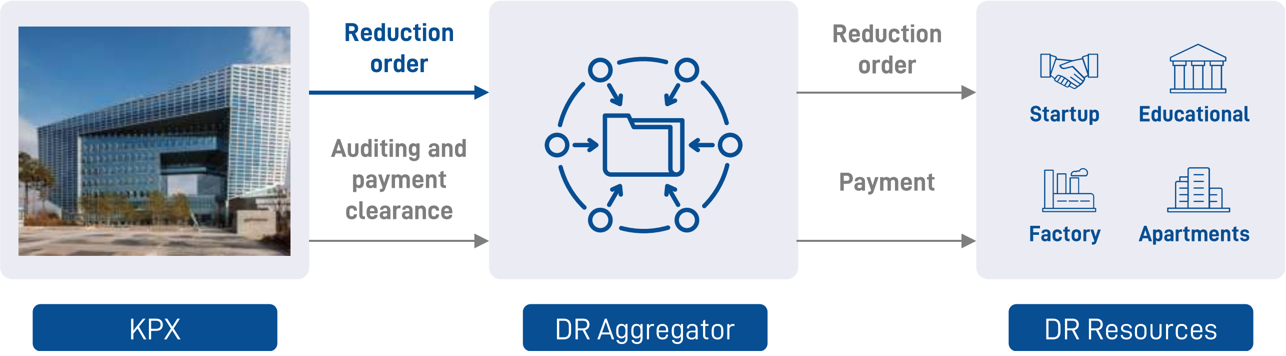
In order to relieve the impact of RE variability, it is necessary to have VRE registered as the system operator's generation resources. Currently there is no effective market mechanism to induce growing number of VRE to participate in the electricity market, and as a result, reliable power system operation becomes increasingly difficult.

As a solution, the power system operator (KPX) is planning to introduce real-time market (RTM) for RE sources. The RTM will allow VRE to bid for electricity supply through the wholesale electricity market. That means VRE are treated with equivalent opportunity and responsibility as conventional generation plants. VRE in the market will have to be obliged to the system operator's dispatch control. In return, they will be remunerated with both energy payment and capacity payment.

3.3.2 Low Utilization of Demand Side Resource for Supply and Demand Balancing

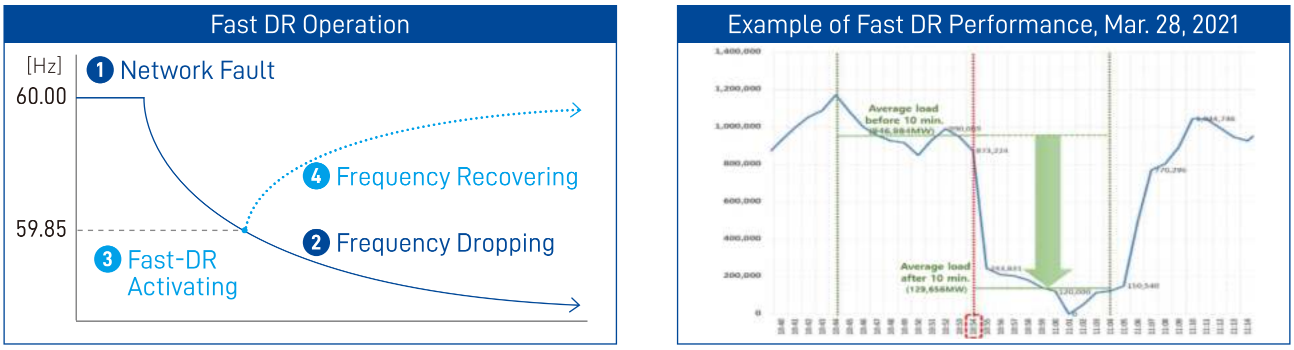
In the context of contingency, demand-side resources can significantly contribute to maintaining a balance between supply and demand. In South Korea, Reliability Demand Response (DR) was introduced in 2014 with the aim of securing demand-side resources to address power system contingencies. Presently, a capacity of 4,894MW from 5,319 customers is actively participating in the Reliability DR market.

Figure 23: DR market operation in South Korea



"Fast DR" was introduced in November 2022, and the program currently involves 710MW of Fast DR capacity from 35 customers. Customers participating in the Fast DR program are mandated to execute Under Frequency Load Shedding (UFLS) for a duration of 10 minutes when the system frequency drops below 59.85 Hz due to VRE trips.

Figure 24: Example of Fast DR operation


Fast DR Operation

Example of Fast DR Performance, Mar. 28, 2021

"Plus DR" was introduced in March 2021 with the aim of incentivizing electricity consumption during periods of VRE overgeneration. Currently, the program involves 181MW of DR capacity from 1,059 participating customers.

Figure 25: Plus DR Implementation Process

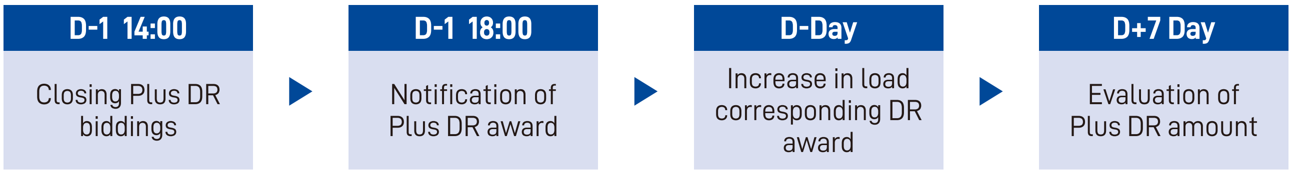


Table 25 presents the performance of Plus DR from March to August 2021. Plus DR was activated for a total of 29 hours, with a contracted volume of 24MWh, contributing 19MWh to VRE generation.

Table 25: Transaction of Plus DR, South Korea (MWh)

Transaction of Plus DR	Total	March	April	May	June	July	August
Bidding Volumes	1,159.87	12.78	119.97	109.62	59.29	62.62	795.59
Contract Volumes	24.27	-	8.06	11.85	-	-	4.36
Performance Volumes	19.48	-	3.22	15.80	-	-	0.47

3.3.3 Supply and demand balancing capacity decrease caused by lack of flexibility resources

With the increasing variability and forecasting errors stemming from the growing number of VRE, the current power system's real-time supply-demand balance capacity is compromised. To bolster real-time balancing, there is a need to revamp the existing electricity market structure to account for the real-time value of electricity. To address this, the implementation of a RTM, operating at 15-minute intervals, is in the planning stages to complement the current DAM, which opens at one-day intervals in South Korea.

An ancillary service market is vital for promoting flexibility resources. Currently, the remuneration for ancillary services is insufficient to encourage flexibility resources to actively participate in the electricity market. Within the ancillary services market, flexibility resources can receive compensation for their contribution to frequency regulation services. This market allows reserve services to be commoditized and traded in real-time (15-minute intervals), enabling prices for reserve services to be determined in real-time through market mechanisms. Consequently, the practical evaluation and compensation of the value of reserve services can be achieved through this approach.

Table 26: Current Payment Schedules for Ancillary Services, South Korea

[Unit: Korean won/kWh]	Regulation Reserve	Primary Reserve	Tertiary Reserve
AS fee	1.08	2.82	2.20

* Total payment for ancillary services: 43.6 billion Korean won/year (0.08% of total electricity market transaction amount, 2021)

Changes Needed to Electricity Market Design

- Improve VRE forecast system to reduce forecast errors
- Open RTM to incentivize VRE to participate in the electricity market
- Introduce ancillary service market to encourage the participation of flexible resources
- Change VRE into a dispatchable generation resources for power system reliability
- Expand DR markets to enhance the power system capacity to respond to contingency

3.4 Power Grid Infrastructure Development

Highlights

Lack of integrated management system (Overlapping agencies: KPX/KEPCO/KEA)	Inefficient VRE management
Insufficient power system infrastructure to respond variability (demand variability 15.6GW)	Supply and demand balancing difficulties
Insufficient power system stability assessment criteria (Reduced power system inertia and strength)	Power system reliability degradation
Insufficient power system capacity to accommodate VRE expansion (time required to build T/D grids 6~8 years versus VRE 1~2 years)	Delayed VRE expansion

3.4.1 Inefficient VRE management due to lack of an integrated VRE management system

In South Korea, there is currently no single agency responsible for the integrated management of VRE, leading to systemic issues in data acquisition, operation, and management of VRE.

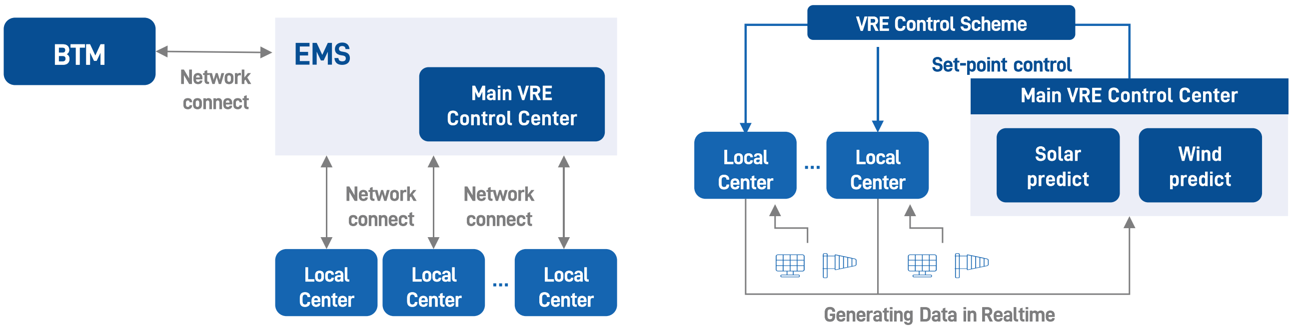
Table 27: Institutions responsible for VRE management in South Korea

Tasks of RE management	KPX	KEPCO	KEA
Data acquisition and management	Electricity market	PPA	BTM (a certain portion of BTM VRE systems)
Trade and payment clearance	Electricity market	PPA	-
Control and operation	154kV or higher	Under 154kV	-

Each agency involved in RE management operates its own data acquisition and management system. The lack of integrated coordination among these agencies leads to duplications and inefficiencies in managing VRE. Currently, KPX, the system operator, can only collect data from 25% of the total installed VRE. This limitation hampers the system operator's ability to effectively respond to the variability of the power system caused by generation plant trips, weather fluctuations, and changes in demand.

By 2030, the variability in VRE generation is expected to increase to 30GW. At that point, the existing VRE management system will likely be inadequate to handle the heightened variability. Therefore, it is imperative to establish an integrated VRE management system under the responsibility of the system operator to ensure more effective and coordinated management.

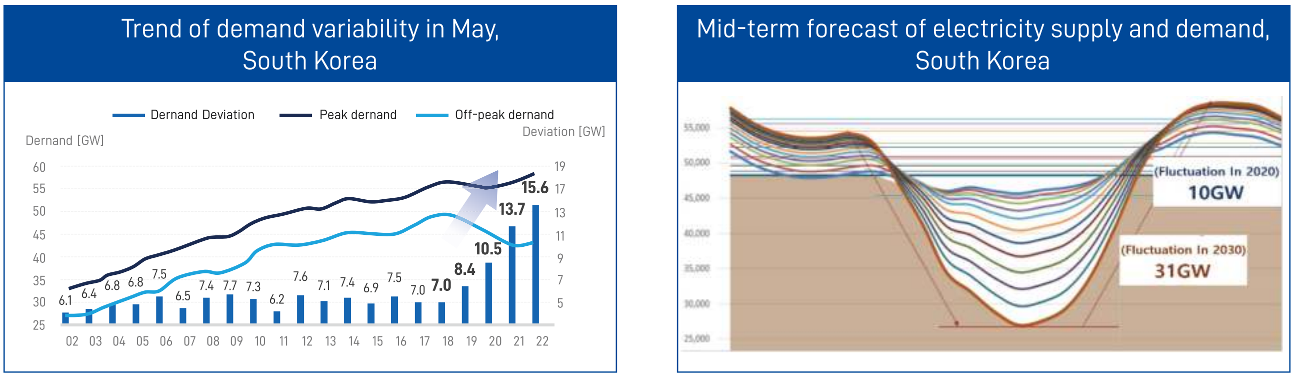
Figure 26: Concept of an Integrate VRE Management system



3.4.2 Supply-demand balance vulnerability due to insufficient power grid infrastructure to accommodate increasing variability

The expected increase of intermittency from growing number of VRE will necessitate back-up facilities. The share of VRE in electricity generation increased from 2.8% in 2017 to 7.2% in 2022, and accordingly, the daily demand variability increased twice from 7.0GW in 2018 to 15.6GW in 2022. By 2030, the variability is expected to increase to 31GW.

Figure 27: Daily power demand fluctuation range and outlook



Trend of demand variability in May, South Korea

Mid-term forecast of electricity supply and demand, South Korea

As the proportion of VRE generation increases, the operation of the power system must transition from relying on conventional generation sources to embracing inverter-based RE sources. The conventional power system operation benefited from high power system inertia, resulting in low-frequency fluctuation and extended frequency response times. Conversely, in an inverter-based power system, operational conditions shift, leading to lower inertia, wider frequency fluctuation, and shorter frequency response times.

This change in the power system's operational dynamics underscores the inadequacy of existing reserve capacity to ensure the reliability of the power system. With the escalating share of VRE, it becomes imperative to design a new reserve system equipped with ample reserve resources to meet the evolving demands of power system reliability.

Table 28: Changing Condition of Power System Operation

	System inertia	Frequency fluctuation	System response time	Reserve capacity requirement
Conventional power system	High	Low	Long (ms)	Fast response reserve (less than 10 seconds)
Inverter based power system	Low	High	Short (μs)	Ultra-fast response reserve (less than 0.1 second)

Table 29: Needed change to reserve criteria in the inverter-based power system

	As-Is Conventional system	**To-Be** Increased RE	**Final** Inverter based system
	Tertiary reserve	Tertiary reserve	Tertiary reserve
30 minutes	Secondary and Frequency Regulation Reserve (AGC)	Secondary and Frequency Regulation Reserve (AGC)	Secondary and Frequency Regulation Reserve (AGC)
5 minutes	Primary reserve(G/F)	Primary reserve(G/F)	Primary reserve(G/F)
10 seconds	-	Ultra-fast response reserve ('23)	Ultra-fast response reserve
2 seconds	-	-	Critical inertia ('25)

3.4.3 Power system reliability degradation due to insufficient stability assessment criteria

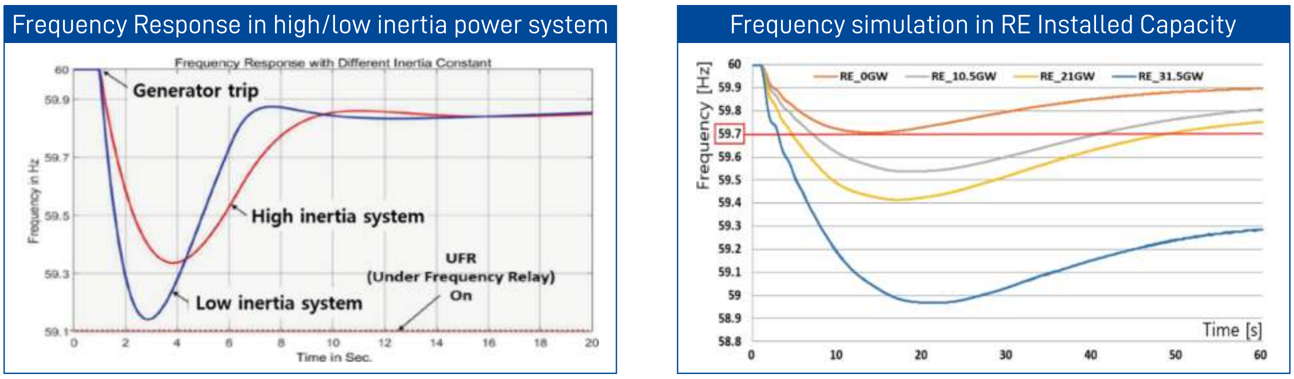
Increased VRE and reduced synchronous generation resources lower the power system inertia and frequency regulation capacity. Therefore, it is necessary to enhance the assessment criteria of power system inertia and to expand additional system capacity.

Table 30: Reliability degradation due to VRE expansion

VRE increase (Solar and wind)	▸	**Synchronous generators decrease** (Coal and LNG)	▸	**Power system inertia reduction** (Spinning inertia)	▸	**Unstable frequency** (power system reliability degradation)

To tackle the issues highlighted above, it is imperative to augment the power system infrastructure by installing additional facilities, such as synchronous condensers and ultra-fast response ESS. Specifically, in the case of Jeju, the system operator establishes the "Must Run" level for thermal power plants to uphold power grid reliability.

Figure 28: Frequency Response in high/low inertia power system and simulation in RE installed capacity

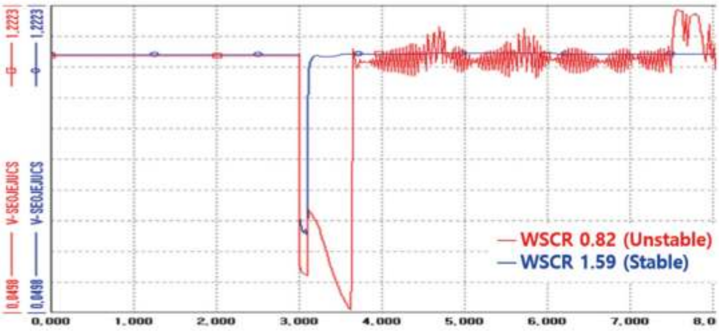


Frequency Response in high/low inertia power system

Frequency simulation in RE Installed Capacity

The shift towards inverter-based power system operation mandates the improvement of power system evaluation and infrastructure. The increasing prevalence of inverter-based generators weakens the overall power system strength, leading to voltage instability. Currently, the SCR is employed as an index to gauge power system strength, with stability typically affirmed if the SCR value falls within the 3~5 range. While thermal power plants usually exhibit SCR values in the range of 4~6, inverter-based systems demonstrate values in the 1~1.2 range, indicating that current inverter-based generators do not sufficiently contribute to power system strength.

Figure 29: Voltage Stability in high/low System strength



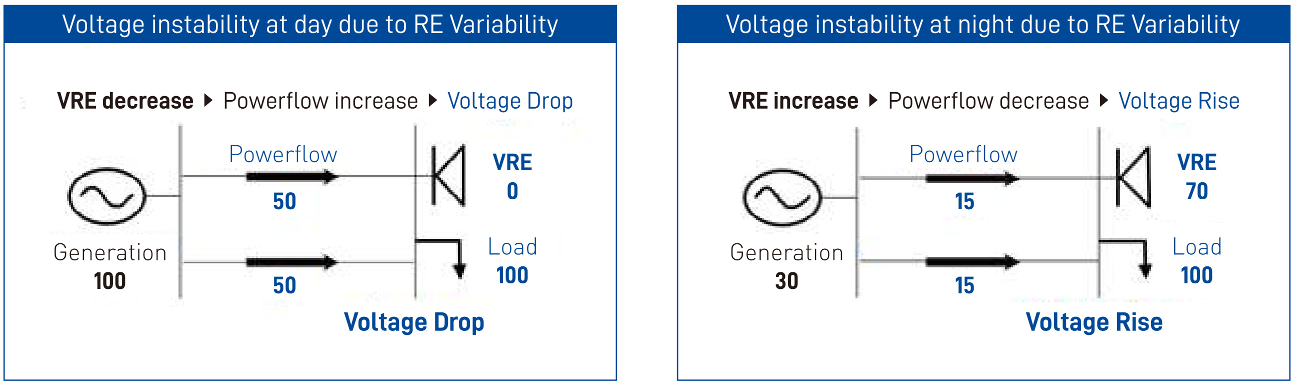
Therefore, to secure the power system strength, the following measures need to be adopted.

- i Redesign the evaluation of power system strength
- ii Improve of power grid infrastructure with synchronous condenser and grid-forming inverters

3.4.4 Insufficient power system infrastructure to accommodate VRE expansion

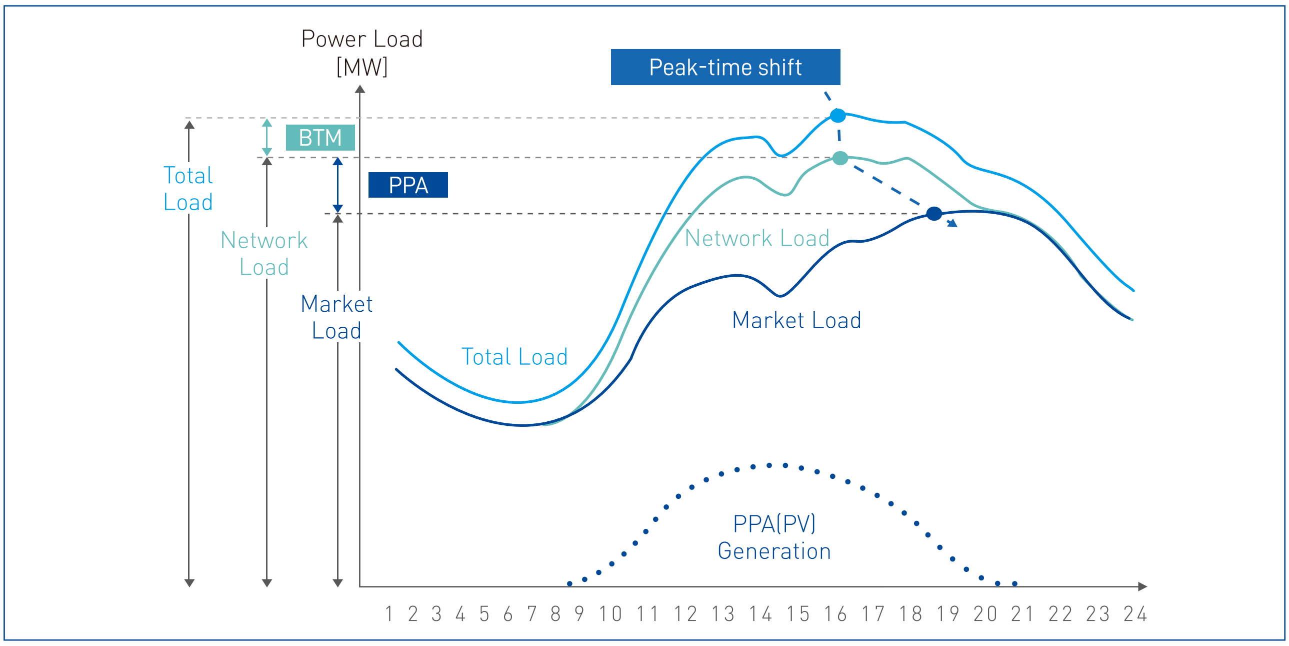
In South Korea, the geographic distribution of VRE is uneven, leading to disproportional deployment. This geographic characteristic, combined with the inherent variability of VRE output, contributes to excessive voltage fluctuations and poses a threat to power grid reliability. Regional dispersion data from May 2022 reveals a disproportionately high share in two southwestern provinces at 43.4% (Jeonbuk Province 19.6% and Jeonnam Province 23.8%). The concentrated presence of RE plants in specific regions raises concerns about voltage instability. A disruption in the power grid may trigger subsequent trips of RE plants, leading to a voltage drop. Consequently, the installation of Flexible Alternating Current Transmission System (FACTS) equipment becomes essential to address voltage variations in the power grid.

Figure 30: Example of voltage instability



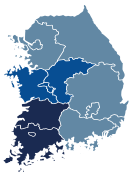
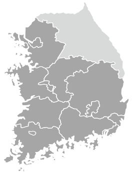
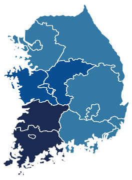
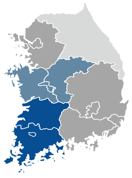
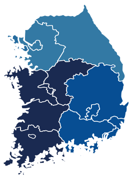
Furthermore, the rapid growth of small-sized RE plants poses challenges for long-term electricity load forecasting. The proliferation of BTM solar PV systems leads to a decline in retail electricity sales to customers, even as the overall electricity demand continues to rise. Although the electricity loads may seem diminished, the total electricity generation is on the upswing. Consequently, a disparity between KEPCO's electricity sales volume and long-term electricity demand predictions, which are estimated based on electricity loads, becomes inevitable.

Figure 31: Change of net-load corresponding VRE Generation



Currently, the absence of a regional-level electricity demand forecasting system exacerbates power grid instability. Therefore, to bolster the power grid's capacity to accommodate VRE increase, it is imperative to implement regional electricity demand forecasting and proactively undertake necessary measures to improve power grid infrastructure. While KEPCO is planning the long-term expansion of transmission substations and lines, the construction of planned power grid infrastructure is experiencing delays due to external factors, including growing resistance from local communities to the construction of power grid infrastructure within their areas. Typically, the installation of VRE takes 1 to 2 years, in contrast to the construction of power grid infrastructure, which requires much longer, around 6 to 8 years. This temporal misalignment exacerbates the challenges associated with power grid infrastructure.

Figure 32: Transmission Congestion problem corresponding RE share in power system

Step	VRE ratio	Network situation	Regional feature	Step	VRE ratio	Network situation	Regional feature
Step 1	≤ 3%	• No overload • Voltage stable		Step 4	30% (3030)	• Enlarge overload • Concern voltage problem	
Step 2	3~15%	• A little regional overload • Voltage stable			40%	• Enlarge overload • Serious voltage problem	
Step 3	15~25%	• Concern overload • A little voltage problem		Step 5~6	≥ 50%	• Serious overload • Serious voltage problem	

Normal

Concern

Serious

* Transmission congestion occurs intermittently 2023, but it will become a chronical problem in 2030

Required measures for power grid infrastructure improvement

- Introduce a single window of integrated VRE management for effective monitoring and control of VRE
- Build back up storage facility to respond to power system variability
  - Secure low carbon and advanced reserve capacity
- Introduce a new power system evaluation
  - A new power grid strength evaluation system and equipment to secure voltage stability
  - FACT (Flexible AC Transmission) system to prevent excessive voltage variations
- Long-term electricity demand forecasting to account for power system variability by VRE
- Enhance power grid infrastructure to accommodate VRE expansion

CHAPTER FOUR.

Recommended Measures

4 Recommended Measures

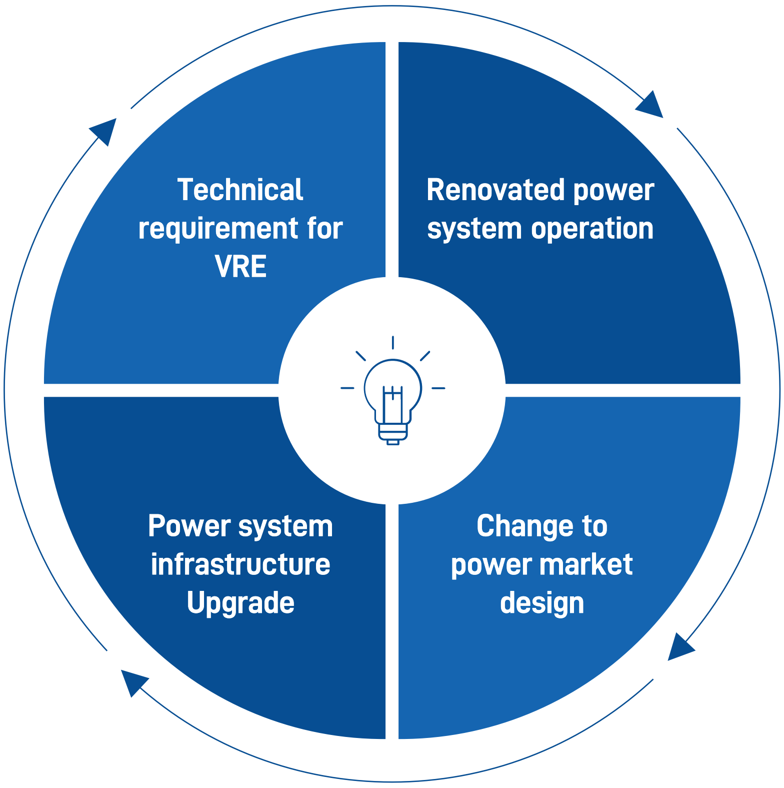
4.1 Recommended Measure: Four Pillars to Secure Power System Reliability

The challenges posed by VRE integration into the power system necessitate a new and comprehensive perspective on power system operation. In South Korea, the established system, built and operated with centralized command structures and economies of scale for generation plants, faces significant challenges to its efficacy. Operational measures that have historically ensured power system reliability are no longer as effective. With renewable energy emerging as a primary source of generation, a new and holistic approach to power system operation becomes imperative.

In each phase of VRE penetration, addressing these challenges requires changes in four dimensions of the current power system operation: i) defining appropriate technical requirements for VRE, ii) adopting a new approach to power system operation, iii) upgrading power system infrastructure, and iv) revising the power market design.

However, before formulating detailed action plans, the initial task for decision-makers in the power market is to comprehend the impacts of increased VRE through a proactive diagnosis of the power system. Given the considerable time lag between VRE deployment and the implementation of changes in the power system to accommodate VRE, it is crucial to assess the effects of increased renewable energy on the power system, taking necessary measures and action plans before actual problems arise.

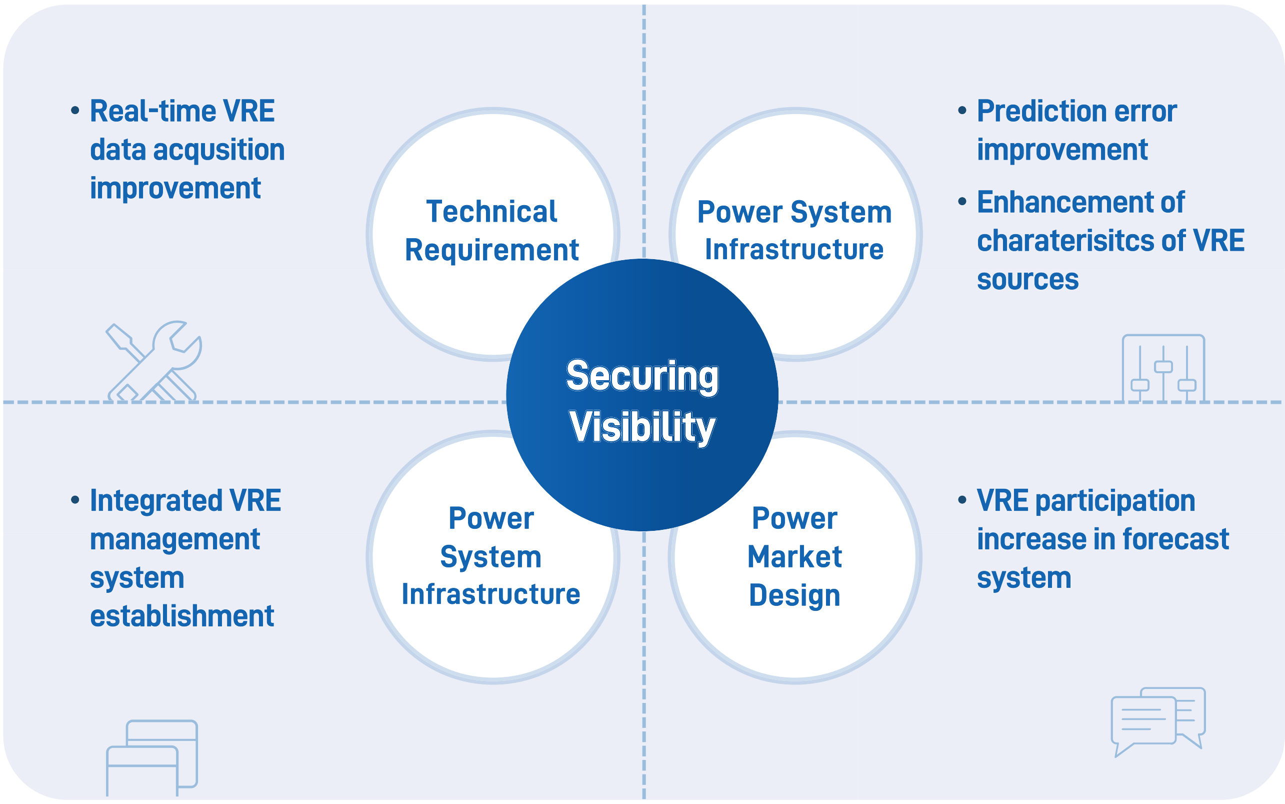
Figure 33: Four Pillars for Securing Power System Reliability



4.2 Measures to Secure Visibility

Securing Visibility of the power system operation through acquiring real-time data of VRE is the key task in early stage of VRE penetration. Securing "Visibility" requires coordinated changes in the entire dimension of power market operation.

Figure 34: Measures to secure Visibility



4.2.1 Real-time VRE Data Acquisition

Real time data acquisition is the key element to secure "Visibility" in Phase Two of the IEA's category of VRE penetration. The VRE data acquisition involves tasks in two different levels of monitoring and reporting of VRE data.

First, individual VRE should be equipped with a proper data monitoring and communication system linked to the power system operator. As mentioned in this report, in South Korea, most of the small solar PV plants are not equipped with a proper monitoring and reporting system that is linked to the system operator's real-time data acquisition system. The government targets to increase the real-time VRE data acquisition rate from 7.5% to 60% by 2025. The 60% is considered as the minimum threshold to achieve statistical confidence in forecast. Therefore, to increase the connectivity of solar PV plants to the system operator's real-time monitoring and data acquisition, there should be policy incentives for small solar PV plants to collaborate with the system operator.

At the same time, the system operator needs to upgrade the current monitoring system. With an enhanced forecast system, the system operator should thereby improve the accuracy of the real-time forecast system for VRE and reduce supply and demand uncertainty.

To mitigate the variability introduced by the rising renewable energy influx, KPX has devised and implemented an ICT-based platform. This system monitors and forecasts the real-time activities of solar and wind energy sources in Jeju.

Image: Jeju Renewable Energy Integrated Monitoring and Control System

Source: KPX Jeju Regional Headquarter

The platform captures and displays the following data and information in real-time:

- Weather conditions and forecasts
- 48 hours wind forecast
- Real-time solar and wind power output
- 24 hour wind output forecast and 6 hours solar power output forecast
- Over generation forecast
- Real-time demand forecast
- Map-based power system monitoring using big data

To enhance the effectiveness of the platform in real-time monitoring and prediction of solar and wind power, an additional sub-system was incorporated. This sub-system is linked to satellite-based cloud and rain information, providing real-time weather conditions. Furthermore, to obtain comprehensive data on variable renewable generation especially small solar PV systems disconnected from KPX monitoring, the platform is connected to KEPCO's database and retrieves information on BTM solar PV activities in Jeju.

Using the platform, KPX aims to ensure the real-time reliability of DES (Distributed Energy System) and enhance the control of power system variability, as well as improve the efficiency of power system operation. KPX plans to continue enhancing the accuracy and effectiveness of the system in monitoring and predicting the behavior of variable renewable energy sources in Jeju. Ultimately, KPX aims to establish a robust "Bid-Data" platform for VRE integration.

4.2.2 Accuracy improvement of VRE generation forecast by prediction algorithm enhancement

Higher penetration of VRE increases the vulnerability of power system operations to climate impacts. The erratic nature of climate changes, coupled with the irregularities introduced by VRE with unmonitored real-time data, intensifies fluctuations in seasonal peak hour patterns.

In response to this challenge, South Korea has outlined a strategy to enhance its demand forecasting algorithm. This improvement entails integrating the generation patterns of unmonitored solar PV plants into the total demand forecast. Moreover, the prediction algorithm will be synchronized with the country's weather forecast system, incorporating real-time weather information into the VRE generation forecast.

As part of its mid-term plan, the system operator aims to bolster the power system's capability to respond in real-time to weather changes by 2025. This involves the development of regional forecast systems based on localized demand data. These systems will receive real-time weather data from multiple satellites, utilize analyzed weather images for forecasting, and provide real-time ramp-alerts. The short-term forecast models, Real-Time (RT) and Operating Time (OP), will be refined to enhance real-time forecasting accuracy.

The ultimate goal is to evolve the VRE forecast system into an advanced real-time prediction system. This advanced system will leverage extended capture of real-time VRE data, real-time image analysis of local weather from multiple satellites, and local solar and wind resources for precise real-time forecasts. With these advancements, South Korea aims to reduce the prediction error rate from 3.3% to 2.9%, positioning itself among the top performers globally.

4.2.3 Management of VRE characteristics data

To control the VRE activity, it is necessary to collect and manage the characteristics data of VRE. Currently, in South Korea, the availability of such characteristics data of VRE is limited. To achieve the level of the statistical confidence of VRE prediction to 95%, the sampling ratio should be 60%. This means the characteristic data from 60% of the total VRE in operation should be collected and managed.

There are a few issues regarding proper management of the characteristics data of VRE. According to the current regulation, VRE already in operation has no obligation of reporting. Only newly installed VRE are obliged to report the plant characteristics data. Therefore, it is necessary to incentivize the existing VRE to report plant characteristics data to the power system operator.

In the short-term, the system operator plans to introduce regulatory changes to expand the coverage of report obligation of VRE. In the mid to long-term, the system operator plans to collect the technical characteristics data of existing VRE using standardized data format and build an integrated data base of all VRE. With the database, the system operator will complete mapping of regional distribution of VRE and develop an up scaling-based forecast model which will support the advancement of VRE forecast system.

4.2.4 VRE controllability improvement with an integrated VRE control system

Another measure to address "Visibility" issue is to improve the controllability of VRE sources. This requires an IT-based system to monitor and control VRE sources connected to transmission or distribution networks. CECRE (Control Centre for Renewable Energies) in Spain is an example of VRE control. CECRE was developed by TSO (Transmission System Operator) in Spain as a part of EMS (Energy Management System) of the country.

From its commissioning in 2006 to the present, the CECRE has been a worldwide pioneer and reference center in the integration of renewable energies in the power system. In the last 15 years, CECRE has allowed a high penetration of renewable energies in Spanish power system by means of the supervision and control of renewable facilities, while ensuring the power supply security. CECRE directly connects VRE IPPs (Independent Power Producers) to TSO so that TSO can effectively supervise and control the performance of individual VRE from the overall power system operation.

As "Visibility" emerges as an urgent issue in the power system operation, South Korea also needs a similar control platform linked to the country's EMS. To develop an advanced VRE control platform, advancements of related technologies are a prerequisite which includes acquisition and processing big-data, and advancement of operating system. Introducing smart inverters with KS (Korean Standards) is also a part of establishment of VRE controllability. Smart inverter is an emerging technology that can help integrated solar power and other distributed energy resources into the power grid. By doing so, South Korea plans to establish a VRE control platform by 2025 and achieve VRE controllability to 75% by 2025 (from currently 0.9%).

In the long-run, South Korea plans to introduce DSO (Distribution System Operator) who, in collaboration with TSO, will be responsible for the optimal power system operation within distribution systems at regional levels. In 2023, the South Korean government enacted a new law regulating DES (Distributed Energy System) and now drafting implementation guidelines, South Korea plans to introduce DSO by 2030.

To develop an advanced renewable energy management system interconnected to the country's EMS, developments in related fields should be accompanied, which include ICT-based convergence technology, big-data and high-speed data processing, and an advanced operational system.

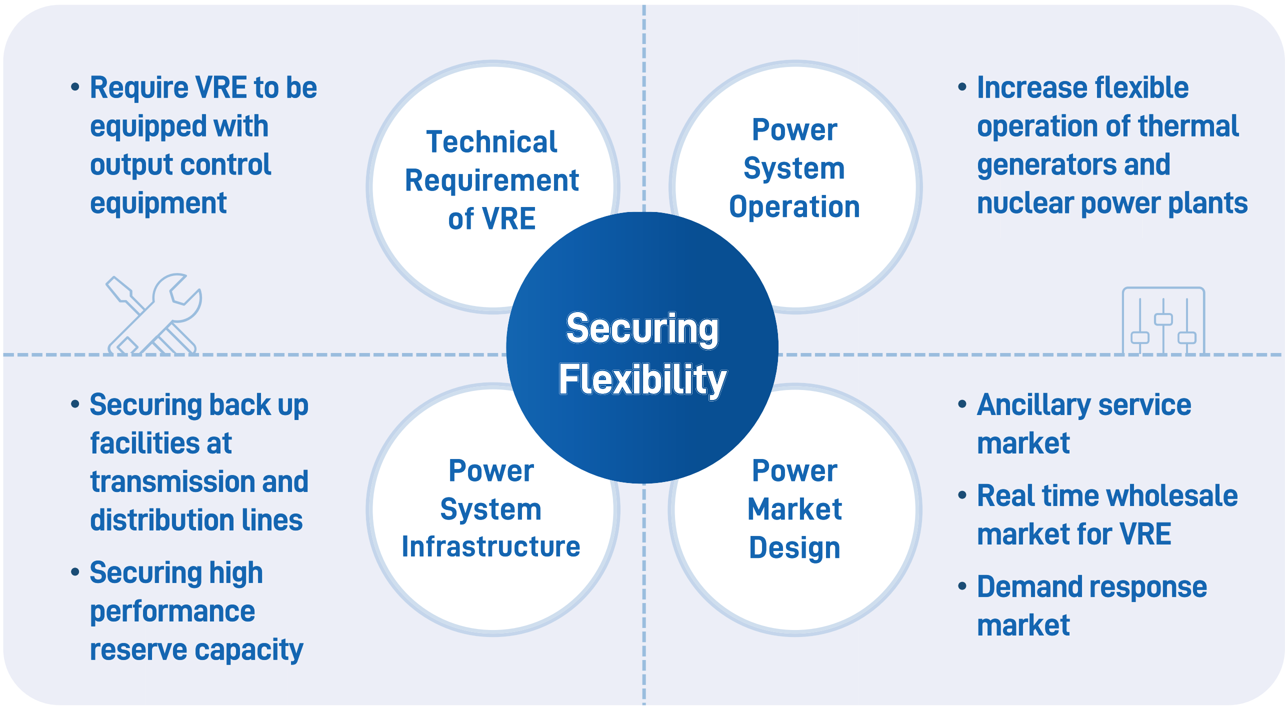
South Korea has implemented a generation forecast system of VRE sources. By May 2022, 1,120MW VRE sources were participating in VRE generation forecast system. This is just 4.46% of total VRE capacity registered in the power market. The low participation of VRE sources in forecast systems leave blind areas in monitoring VRE activities, and results in increased prediction errors of VRE generation.

To increase participation of VRE sources in the forecast system, change to the power market operation is necessary including financial incentives for VRE sources participating in the forecast system. Eventually, the management of VRE sources in the power market should be changed from the current forecasting system to a new electricity market system in which VRE sources participates in biddings as a dispatchable source in the real-time wholesale electricity market.

4.3 Measures to Secure Flexibility

Securing Flexibility of power system operation is the key task in Phase Three of VRE penetration. Flexibility in the power system operation can be achieved by flexible operations of conventional generation plants as well as adding new flexibility resources both at supply and demand of sides.

Figure 35: Measures to secure Flexibility



4.3.1 VRE output control

Currently, majority of VRE, especially small solar PV plants are not equipped with output control equipment. Therefore, it is necessary to introduce policy incentives to make VRE have proper control equipment. The South Korean government plans to introduce KS (Korean Standard) smart inverters which have enhanced grid-connection performance by 2024. Once the policy of KS smart inverters is introduced in 2024, all new VRE facilities should have output control functionality. However, existing VRE need a separate measure to secure output controllability.

4.3.2 Flexibility operation of thermal and nuclear power plants

As the share of VRE increases, the fluctuation of the netload level increases too. In South Korea, nuclear and coal power sources share 29.6% and 32.5% of electricity generation respectively in 2022, and these two main generation sources face challenges in adjusting to the fluctuating netloads.

In South Korea power system, nuclear power plants are exempted from AGC (Automatic Generation Control) or GF (Governor Free) modes of operation. In contingency, the adjustment of operational level of nuclear power plants are, therefore, made manually. In 2022, nuclear power plants in South Korea conducted ramp-rate control only six times, and five of them were planned controls. One was the emergency ramp-down in response to a wildfire accident.

Now, there is no regulation of technical requirements and safety measures of output control of nuclear power. Therefore, it is necessary to draft regulations governing ramp control of nuclear power plants. Organizing an experts committee and hearing process is recommended to draft such regulation.

In France where 58 units of nuclear power plants share 71.7% of electricity generation (2018), 5~10% of the nuclear power plants are designed to perform load-following operation. The system operator controls the load-following operation units based on loads and adjustable operational capacity of the nuclear power plants.

Germany, for another example, where 23 units of nuclear power plants are in operation, the load following operation of nuclear power plants becomes important to respond to intermittency of VRE. In Germany, nuclear power plants are designed to perform load following operation in various modes with maximum 5% ramp rate adjustment. Latest nuclear power plants are designed with maximum 14% ramp control capability.

In the long-run, South Korea should require flexible operation to all new nuclear power plants entering the electricity market. For this, it is necessary to build human and technical capacity for optimized power system operation. In the future power system, nuclear power plants should be designed to collaborate with VRE and demand-side resources and operate flexible way to respond to fluctuating load curves.

In case of thermal generation, in South Korea, only a limited number of generators show proper ramp control performance. Majority of thermal generators are old units, and not able to perform flexible operation due to multiple internal operational constraints including minimum output limits, operational problems of environmental equipment, and lost profits due to reduced generation.

To improve the flexible operation of thermal generators, it is necessary to introduce policy incentives to promote flexible operation of thermal power plants and develop new air pollution control technologies for thermal generators.

4.3.3 Flexible back-up facility and reserve capacity at transmission and distribution grids

As VRE increases in power generation, various flexibility resources are required to respond to increasing variability of power system operation. Flexibility resources include reserve capacity, energy storage, and demand-side resources.

Energy Storage

According to the 10th BPLE (Long-term Basic Plan for Electricity Supply and Demand), renewable energy including hydropower is expected to become a major generation source in the power system with share in electricity generation of 21.6% in 2030 and 30.6% by 2036. Given that the share of hydropower remains only at 1% level, most of the expected renewable energy generation comes from VRE sources, solar and wind power.

ESS (Energy Storage System) is a very useful flexibility resource for VRE. Right now, PSH (Pumped Storage Hydropower) and BESS (Battery ESS) are considered economically efficient and technically proven technologies to secure power system flexibility to host penetration of VRE. South Korea has limited hydro resources. Hydropower shares just 1% of the total power generation. By the end of 2022, South Korea has 4.7GW PSH capacity in operation. On the contrary, South Korea is among the global leaders in lithium-ion battery manufacturing. By the end of 2022, South Korean government already supported deployment of more than 10GWh BESS in the power system which include BESS at transmission grids for frequency regulation, BESS linked with VRE for energy storage and dispatch, and BESS for peak demand sharing.

As the costs of BESS declines, BESS is expected to be a major component of flexibility resources in power system operation around the world. BESS has been proven effective in frequency stabilization in the event of a grid fault, mitigating the variability of VRE output, and reducing VRE curtailment. BESS also can be used to reduce transmission congestion.

According to the 10th BPLE, South Korea will need additional 23.6GW ESS capacity by 2036. Among them short duration 3.66GWh ESS capacity is needed for short duration applications, and 22.6GWh capacity is needed for long-duration applications. Short duration ESS is to respond to the power system variability in 30 minutes. The long duration ESS is to absorb surplus renewable energy generation in daytime and discharge it in night-time. The storage requirement of long-duration ESS is 4 to 6 hours.

Table 31: Expected ESS Capacity Requirements by 2036

Period	2023~2026	2027~2030	2031~2036
Short Duration(GW)	0.05	1.16	3.66
Long Duration(GW)	0.16	3.1	22.6
Total(GW)	0.21	4.26	26.3

Source: ADB Energy Transition Workshop in Seoul, Hyung-Tae Kim, KPX, October 2023

In the 10th BPLE, PSH will contribute 1.8GW by 2034. Therefore, the remaining of 24.5GWh ESS(26.3GWh minus 1.8GWh) should be constructed from other technologies. Given the cost competitiveness and proven technology, lithium-ion BESS is expected to contribute much of the required ESS capacity. At the same time, on the long-term perspective, South Korea should develop other ESS technologies. Green hydrogen is a focused target to be developed as a long-duration storage solution on the long-term horizon.

High performance and low-carbon reserve capacity

Current power system in South Korea keeps enough inertia, and the power system is operated with generation plants controlled by the system operator. However, expected increase of VRE will reduce the system inertia and therefore new measures are required to secure reserve capacity to supply necessary system inertia in contingency events.

In order to address the issue, South Korea plans to introduce super-fast response resources at transmission lines for frequency regulation. The super-fast response resources is likely to be lithium-ion ESS in short-duration. In the long-run, it is necessary to change the power system operation from current synchronous generators as the main power system reserve to high performance low carbon reserve capacity.

Currently, there is no proper remuneration schemes for ancillary services in South Korea and this limits participation of new reserve resources in the electricity market. Therefore, it is necessary to make changes to the power market design to facilitate the participation of diverse reserve capacities to the power market.

4.3.4 New markets for ancillary services, VRE in wholesale market and demand response resources

Real-time electricity market to promote VRE

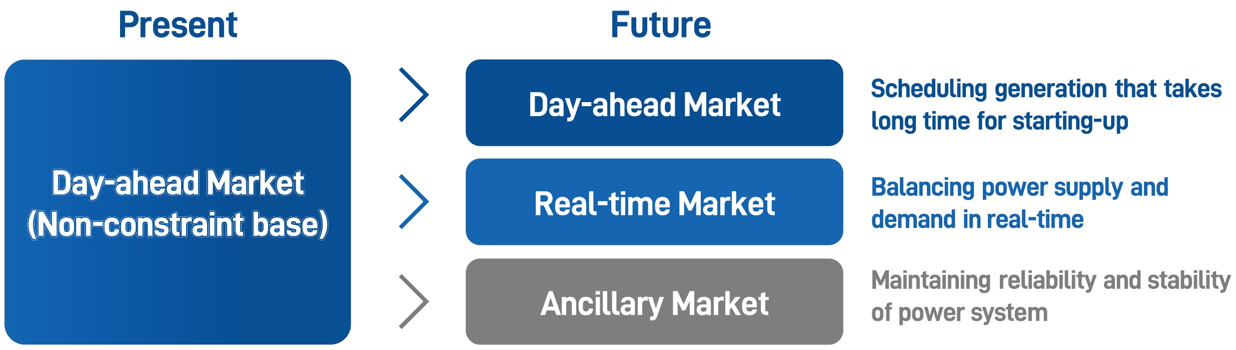
Current wholesale electricity market in South Korea is Day-ahead Market (DAM). DAM market is limited to incorporate real-time prices and to respond to real-time supply and demand changes. In 2023, the system operator introduced a pilot real-time market (RTM) in Jeju Island. The purpose is to open a market for renewable energy biddings. Once the pilot market is proven effective in responding to increased VRE, especially small-scale solar IPPs, RTM is planned to be implemented on a nationwide basis from the end of 2025.

In RTM, the prices and electricity trades will be determined every 15 minutes. The purpose of introducing real-time market is to balance a real-time power supply and demand. In RTM, generation units exceeding 1MW are obliged to match real-time supply and demand balance as a dispatchable generation source. In RTM, renewable energy plants will be compensated for participating capacity as well as for energy supply. Individual VRE IPPs are encouraged to collaborate matching energy sources to develop VPPs (Virtual Power Plants) and participate in RTM with a firm capacity.

Ancillary service market

In addition, ancillary service market is necessary to promote flexibility resources. Currently, the remuneration for ancillary services is too low to incentivize flexibility resources to participate in the electricity market. In ancillary services market, flexibility resources can be compensated for their contribution to frequency regulation services. In ancillary service market, reserve services can be commoditized and traded real-time (15 minutes intervals), and the prices for reserve services can be determined real-time through the market mechanism. Thus, the value of reserve services can be evaluated and compensated in practical ways.

Figure 36: Needed Changes to Power Market Design



Note

1) Day-ahead Market (constrained/unconstrained market): Providing price signals to long start-up time generation units for the wholesale market participation

2) Real-time market: Balancing real-time demand and supply

3) Ancillary market: Providing ancillary services for power system reliability and frequency regulation

DR (Demand Resource) market

As for the demand side, South Korea has actively promoted demand response resources. From 2014, South Korea introduced a market-based DR (Demand Response). In the market-based DR, an aggregator collects DR resources mostly from large industrial and commercial electricity users and bid the collected DR sources in the DR market. The market-based DR was very successful and by the end of 2022, 5,319 electricity users registered 4,894MW DR sources. In addition, South Korea introduced Fast DR and Plus DR. Fast DR is a demand-side resource to respond to frequency drops, and Plus DR is an incentive program for EVs. EVs participating in Plus DR are offered lower charging fees in an event of VRE overgeneration.

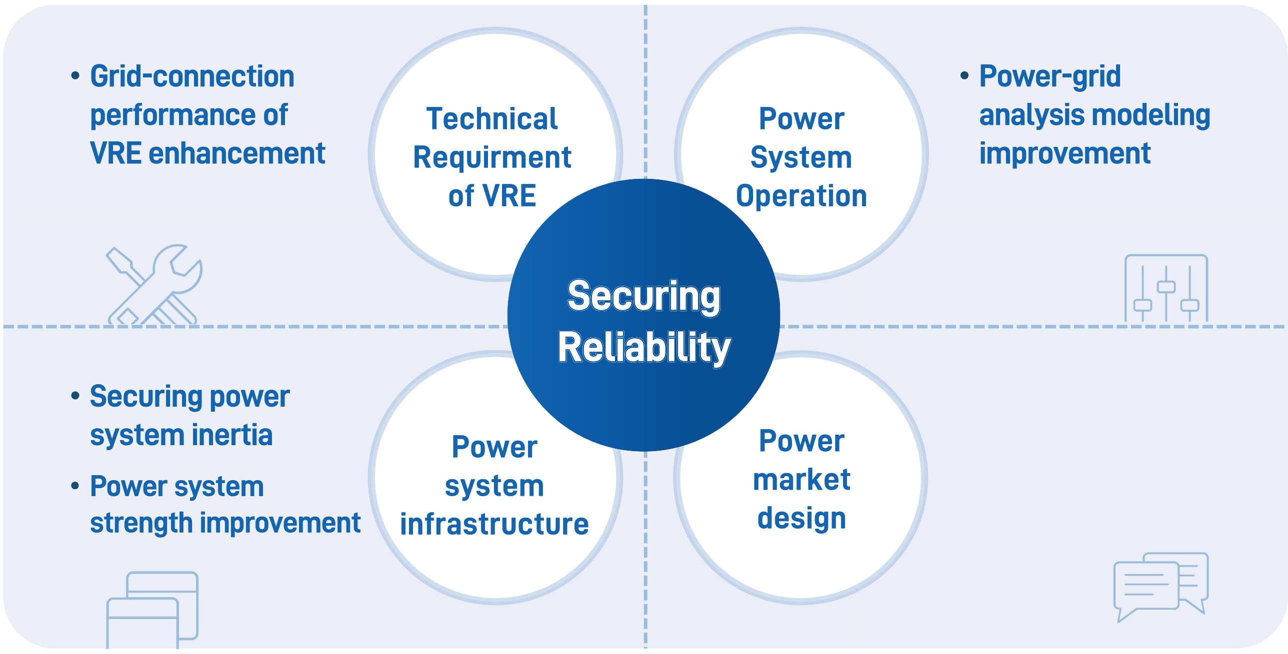
Since 2017, the market-based DR shows flattened increase of participation. This is because large electricity users from energy intensive industry are already in the DR market, and there is no significant marginal effect of the capacity of new DR resources entering the market.

To increase DR capacity, therefore, it is necessary to design policy incentives to identify and invite available DR resources to in the DR market.

4.4 Measures to Secure Reliability

Securing Reliability of power system operation is the key task in Phase Four of VRE penetration. Flexibility in the power system operation can be achieved by flexible operations of conventional generation plants as well as adding new flexibility resources both at supply and demand of sides.

Figure 37: Measures to secure Reliability



4.4.1 Securing grid-connection performance of VRE

Many solar PV plants in South Korea lack proper grid-connection codes, including Fault Ride Through (FRT) and Low-Voltage Ride Through (LVRT), leading to power system instability. This deficiency in grid-connection codes can trigger system-wide shutdowns if there's a failure in the power system, causing subsequent trips of VRE.

To prevent operational interruptions of VRE generators during short-term abnormal voltage or frequency events in the power grid, it is essential to ensure the grid-connected performance of VRE. This involves implementing preemptive measures to protect power system stability by continually strengthening the grid code of VRE in response to changing levels of VRE penetration.

In South Korea, the configuration of solar PV inverters has become a critical issue. Historically, these inverters lacked settings to protect them from power grid accidents. As the share of VRE increases, concerns about power grid instability grow. To address this, a policy was introduced in 2021, requiring solar PV inverters to have settings that protect against spill-over problems from the power grid. However, inverters installed before this policy are at risk of shutting down during power grid accidents.

A recent government survey in Jeju Island revealed that 54% of operating solar PV inverters need to change their settings. It's reasonable to assume that similar conditions exist on the mainland. With 17.53GW of solar PV operating on the mainland, approximately 9GW of solar PV inverter settings may need modification. The system operator plans to recommend government intervention to enhance grid codes for VRE systems, particularly in areas vulnerable to the impact of VRE. Gradually, these changes need to be extended to all VRE systems. (Reference: Man-Geun Park, KPX, ADB Workshop for Clean Energy Transition in GMS, October 2022).

4.4.2 New power system analysis modeling

VRE, being inverter-based systems, have altered the dynamics of the power system, leading to increased instability. The evolving nature of the power system environment demands a modified approach to power system analysis and modeling.

Table 32: Changed power market condition and needed changes to power system analysis model

Changing power market condition		Needed changes to power system analysis model
○ RE as the main generation source ○ Dynamics changes of power system: fast response, and interferences ○ New concept of power system reliability, for example resonance and converter drive	➡	○ Increase the portion of inverter model in response to reduced synchronized unit model ○ Introduce EMT-based power system analysis ○ Improve the reliability of the power system analysis in response to increased complexity of power system

However, currently there is no established mechanism for modeling inverter-based power systems. Major power system analysis software suppliers such as GE or Siemens provide generic analysis models without detailed guidelines for inverter-based system modeling. While traditional power system modeling tools like PSS/e are effective for millisecond to second analyses, inverter systems respond much faster. Therefore, advanced tools capable of analyzing operational data in microseconds to milliseconds are required for inverter-based power system analysis.

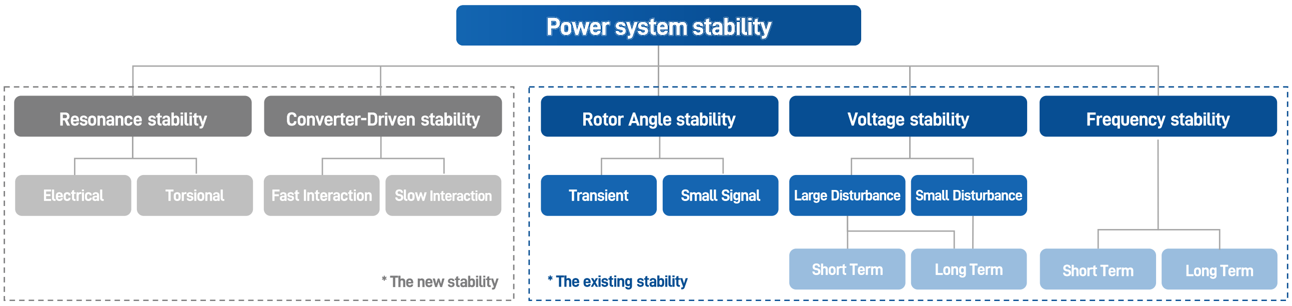
Although some private vendors offer customized power system analysis tools, their credibility is yet to be proven. The increasing complexity of power system analysis, driven by the growing number of inverter systems, highlights the need for expanded human and research infrastructure in this field.

To establish a reliable modeling framework for inverter-based power system analysis, the development of an advanced evaluation system is crucial. This system should be capable of analyzing and evaluating new electric-power facilities, including High Voltage Direct Current (HVDC), Flexible Alternating Current Transmission Systems (FACTs), and Energy Storage Systems (ESS). Additionally, building human and research infrastructure is essential, and this can be achieved through industry-academia partnerships and knowledge-sharing initiatives among countries.

Establishing the instantaneous data-based power system analysis modeling

As VRE increases, counterinfluences increase among new electric-power facilities (HVDC, Inverter-based resources, and FACTs). As a result, IEEE added new definitions and classifications, 'resonance stability' and 'converter-driven stability', to the existing classification of power system stability.

Figure 38: Classification of Power System Stability



Source: IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 36, NO. 4, JULY 2021 3271
"Definition and Classification of Power System Stability – Revisited & Extended"

In a power system with high VRE penetration, traditional RMS (Root Mean Square) based power system modeling proves ineffective due to its inability to capture the dynamic characteristics of new facilities operating in a non-linear manner and at microsecond intervals. Therefore, as VRE takes a prominent role in power generation, transitioning to EMT (Electromagnetic Transient)-based power system modeling becomes essential.

The power system operator in South Korea has outlined plans to develop and enhance EMT-based power system analysis modeling. Eventually, the current RMS-based power system analysis modeling will be phased out in favor of EMT-based modeling to better accommodate the evolving dynamics of the power system.

4.4.3 Upgrade of Power System Infrastructure

Secure power system inertia

IEA(International Energy Agency) has defined securing power system inertia as a crucial task for sustaining frequency stability in Phase Four. VRE, lacking inertia, diminish the system's ability to regulate frequency, reducing overall system inertia. For instance, to maintain system inertia despite increased VRE, the system operator in Jeju Island designates a certain capacity of thermal generators as "Must-run" generators.

Given the unique characteristics of South Korea's power system, a proactive approach is necessary to secure power system inertia even in Phase Two of VRE penetration. In the short term, the system operator will assess the required reserve capacity to uphold power system inertia and incorporate this into the country's long-term generation expansion plan. Additionally, plans include enhancing the accuracy of monitoring and evaluating system inertia.

In the mid to long term, diversification of system inertia resources is essential. New technologies, such as ESS and synchronous condensers, should be developed and utilized for system inertia. Furthermore, changes to the power market system are proposed to encourage the utilization of diverse inertia resources.

Secure power system strength

System strength is a characteristic of an electrical power system that relates to the size of the change in voltage following a fault or disturbance on the power system. Power system strength is seen as the ability of the power system to maintain and control the voltage waveform at any given location in the power system, both during steady state operation and following a disturbance (System Strength, March 2020, Australian Energy Market Operator).

Power system strength is measured with SCR (Short Circuit Ratio) or WSCR (Weighted SCR). The bigger the SCR, the higher the strength of a power system. While a thermal power plant in general provides SCR value at 5 to 6 times of its nominal capacity, the SCR value of an inverter-based system is only 1 to 1.2 times of its nominal capacity. Therefore, increased penetration of inverter-based systems reduces the power system strength. Unlike synchronous machines, inverter-based systems provide a significantly lower and different contribution to the power system strength, which means that the lowest system strength on a power system is likely to be in a part where generation is dominated by inverter-based systems.

Table 33: Measures of Power System Strength

System Strength	SCR Value	WSCR	Power system Status
High	>3	1.5>	Stable
Low	2 ~ 3	1.5<	Vulnerable
Very Low	<2		Measures need to be taken

* Note: The Power System Evaluation is based on IEEE 1204(1997) Guideline

Lower SCR causes voltage instability even at small impacts on the power system and can cause system-wide blackout. To secure the power system strength, it is necessary to monitor power system strength; evaluate the needed capacity of strength resources and identify and analyze locations of strength resources; and account for the needed capacity into the long-term generation expansion plans. Also, it is necessary to diversity strength resources, develop new technology, like grid forming inverters, to utilize system strength resources, and make necessary changes to the power market design to facilitate the participation of diverse system strength resources.

Secure Dynamic Reactive Power

Other measures to address voltage instability caused by high VRE penetration is securing dynamic reactive power in the power grid. To secure voltage stability and power system reliability, South Korea targets to secure 14GVAr dynamic reactive power by 2030. The measure needs to introduce FACTS (Flexible AC Transmission System) facilities.

Until necessary reactive power is obtained, intermediary measures are needed to secure the system stability especially in local areas where VRE are concentrated. Those intermediary measures include generation curtailments, and generator cut-off SPS (Special Protection System) to be activated in case of transmission line troubles, and measures to secure flexible VRE generation in case of overgeneration.

Establish long-term electricity demand forecast system

Increased VRE causes demand forecast errors. Until the 9th BPLE(2020), the electricity demand forecasts were made based on the peak demand data and electricity consumption data measured by the volume of electricity sales collected by KEPCO. However, as the number of BTM solar PV systems increases, the electricity sales by KEPCO decreases. Due to the increase of the small solar PV systems in blind areas, peak demands appear to be decreasing. The missing data in the blind areas can distort demand forecast statistics and increases the fluctuation of load curves.

In South Korea, the BPLE based on demand forecast is completed on the country level. Therefore, demand forecasts errors and power system variability can be severe in areas where VRE are concentrated.

In order to minimize such distortion in demand forecast and improve the accuracy of demand forecasts, the system operator plans to take the following measures.

i Introduce regional demand forecast systems in parallel with the national demand forecast system.

ii Modify current demand forecast system to account for missing data of electricity generation from BTM solar PV systems.

iii Establish total electricity demand data-base and long-term load curves.

Table 34: Trend of total electricity consumption in South Korea (Unit: GWh)

Category	2010	2015	2020	Annual average growth [%]
Total Electricity Consumption	453.0	502.7	535.4	2.4
Electricity sales by KEPCO	434.2	483.7	509.3	2.3
	(95.8%)	(96.2%)	(95.1%)	
Self-generation and consumption	18.8	19.1	26.1	3.9
	(4.2%)	(3.8%)	(4.9%)	

Improve the power grid infrastructure development plan

As the share of VRE increases in the power system, the timely expansion of power grid infrastructure emerges as a critical issue. The current planning framework, consisting of two master plans—the Basic Plan for Long-Term Electricity Supply and Demand (BPLE) and the Long-term Transmission and Substation Facility Plan (TSEP)—serves as the foundation for power grid infrastructure development. The BPLE outlines the overall plan for generation expansion, while the TSEP provides detailed plans for transmission and substation construction. However, in the existing long-term power grid infrastructure planning system, the TSEP is developed after the finalization of the BPLE, meaning that the planning for transmission line construction follows the generation expansion plan. This traditional approach does not align with the evolving conditions of new power system development, especially with the increasing integration of VRE.

As VRE becomes more prominent in the power system, it is crucial to synchronize the long-term planning of power system development with the time lags between the development of VRE plans and the necessary power grid infrastructure. For example, while solar PV systems can be constructed in an average of 1 to 3 years, planning and constructing a transmission line takes 6 to 8 years. These time lags can lead to insufficient transmission and substation capacities to accommodate VRE sources, resulting in serious congestions at transmission lines.

To address these issues, a proactive approach to power grid infrastructure development is necessary. Eventually, the BPLE and the TSEP should be integrated into a consolidated master plan. Additionally, regional zone planning for VRE development should carefully consider the conditions of transmission and substation infrastructure. In the long run, exploring the participation of private entities in the transmission and substation infrastructure business may be a viable option.

4.5 Recommended Actions in Each Phase of VRE Penetration

The table below summarizes the recommended actions to be taken at each phase of VRE penetration. These proposed actions aim to contribute to the development of a comprehensive carbon neutrality master plan, outlining specific steps to be taken in each phase. This master plan and its associated actions are anticipated to enhance the visibility, flexibility, and reliability of the power system in South Korea. Moreover, these efforts will contribute to ensuring the reliability of power system operations, particularly in Jeju.

Table 35: Recommended Actions to Secure Power Grid Reliability for Increased VRE

Category	**As-Is** Conventional system	**To-Be** RE based system	Anticipated problems	Actions	
				Actions	Goal
Unit capacity	≥100MW	≤1MW	Visibility ▼, Manageability ▼	Expand real-time monitoring and data acquisition equipment	Securing Visibility
				Enhance technical norms and grid codes for RE systems	
Number of Generation plants	≤1,000	≥100,000		Introduce an integrated RE management system	
Supply capacity	Fixed	Variable	Uncertainty ▲	Improve RE generation forecast	Increasing Flexibility
				Introduce regulation for RE generation forecast	
			Variability ▲	Open RTM (Real Time Market)	
				Secure back-up facilities for flexibility and storage	
Output control	≥20% (possible)	≃0% (impossible)	Controllable resource ▼	Enforced RE generation control	
				Introduce scheduled control of nuclear power plants operation	
				Improve flexibility of thermal power plants	
				Open ancillary service market	
Reserve capacity	Available	Not available		Enlist RE plants on the system operator's generation fleets	
				Expand DR market and DR resources	
				Secure high performance, low carbon reserve capacity	
System inertia	4~6s	≃0s	Frequency stability ▼	Secure FRT of RE systems	Improving stability
				Enhance power system evaluation and infrastructure	
System strength (short circuit ratio)	Strong (5~6)	Weak (≃1)	Voltage stability ▼	Develop inverter-based power system analysis modeling	
				Establish EMT-based power system analysis platform	
				Enhance power system strength assessment and power system infrastructure	
				Expand the spinning reactive reserve facilities	
Improve infrastructure	Long-term (6~10 years)	Short-term (1~2 years)	Transmission congestion ▲	Establish long-term demand forecast system	
				Improve regulation for power infrastructure	
Jeju Power System			Reliability ▼	Improve power system reliability	Improving Reliability
			Over generation ▲	Reduce RE curtailments	

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