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Cost Analysis of Solutions to Renewable Curtailment on Jeju Island, South Korea

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Solutions for Our Climate (SFOC) is a nonprofit organization established in 2016 for more effective climate action and energy transition. SFOC is led by legal, economic, financial, and environmental experts with experience in energy and climate policy and works closely with domestic and international partners.

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

Jeju's 2030 Carbon-Free Vision Begins With Renewable Curtailment Freedom:

Cost Analysis of Solutions to Renewable Curtailment on Jeju Island, South Korea

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Executive Summary

In 2012, Jeju Special Self-Governing Province of South Korea declared its vision to become an island with net zero emissions by 2030, initiating a project dubbed "Carbon Free Island Jeju 2030", or CFI 2030.[1] Since then, Jeju has seen such a rapid proliferation of new and renewable energy facilities that the proportion of new and renewable energy reached about 18 percent of the island's power generation in 2020.[2] The fast penetration of renewables, however, has inevitably entailed a sharp rise in curtailment.

The amount of power instantaneously fed into an electric power grid (the amount of power generation per unit of time) must equal the amount of power that comes out of the system (the amount of power consumption per unit of time). When an oversupply of power (excess power generation) is expected, the Korea Power Exchange (KPX) orders power producers to reduce their generators' output to eliminate any supply-demand mismatch, thereby preventing grid instability. This measure is called curtailment. KPX recently proposed an amendment to its Rule Revision Committee to require renewable energy facilities to comply with KPX's curtailment measures.[3]

Jeju began to experience curtailment issues earlier than the Korean mainland because renewables account for a relatively higher share of the island's power generation. Curtailment is expected to grow more common in power grids throughout the country, with grids in Sinan, South Jeolla Province,[4] already instituting curtailment due to the area's growing renewable energy generation.

Jeju has begun reining in the penetration of renewables by considering the implementation of a cap on total new and renewable energy generation,[5] but such an approach will not only impede the country's transition to a renewable-based power grid but also delay progress to achieve the ultimate goal of carbon neutrality.

1 JIN Sun-hyeon, "Jeju Announces 'Carbon Free Island Jeju by 2030' for Green Growth." Aju Business Daily at https://www.ajunews.com/common/redirect.jsp?newsId=20120502000427, accessed on Sept. 6, 2022
2 KIM Yeong-hwan, "Implications of Excess Renewable Energy Generation on Jeju Island" [presentation at a conference], Direction of Power Market System Improvements for Net Zero by 2050 by the Incoming Government: A Renewable Energy Curtailment Seminar. Seoul, Republic of Korea.
3 YUN Dae-won, "Confrontation Between KPX and Renewables Producers Over Obligatory Curtailment," The Electric Times at https://www.electimes.com/news/articleView.html?idxno=308054, accessed on Sept. 6, 2022
4 JEONG Hyeong-seok, "Solar Curtailment Began Even in Non-Jeju Region," The Electric Times at https://www.electimes.com/news/articleView.html?idxno=214432, accessed on Sept. 6, 2022.
5 GANG Seung-nam, "55 Shutdowns in 1st Half Alone ... Jeju Is to Introduce NRE Capacity Cap," News 1 at https://www.news1.kr/articles/?4371895 accessed on Sept. 6, 2022

Against this backdrop, we considered the total system cost (TSC) of Jeju's power grid across two scenarios of maintaining a high renewable energy target under the Ninth Basic Electricity Plan (CFI 2030 Plan) while keeping curtailment to a 3-percent level. The TSC of two scenarios will be compared against the TSC of the Business as Usual (BAU) plan, to examine whether following either scenario would incur excessive cost.

Four essential elements are considered in this report's technical scenarios to minimize the island's curtailment in renewable energy: Jeju's renewable penetration plans, its incoming and outgoing high voltage direct current (HVDC) capacity, fuel prices, and replacement of "must-run generators" (generators that must be operated) by synchronous condensers. By calculating the optimal storage system investment and accordingly predicting the total system cost (storage system installation, power generation fuel, and carbon price), cost-benefit analysis was conducted for each scenario. We then also indirectly considered the profitability of power producers by analyzing the trends in the utilization rates of fossil fuel-based power plants and renewable energy generators under each scenario. Our analysis yielded the following significant conclusions:

First, Jeju Island can achieve the CFI 2030 goals and meet the renewable energy expansion targets under the 9th Electricity Supply and Demand Master Plan while maintaining a curtailment rate at 3 percent. To this end, it is necessary to replace three of the fossil fuel-based must-run generators that are currently in use on Jeju Island with synchronous condensers, and to introduce other flexibility resources, including storage systems with a capacity level of 1,151 MW by 2034. We have confirmed that such measures will help secure resources required for system reliability and, therefore, help raise the penetration of renewables per the CFI 2030 scenario with synchronous condensers while maintaining a curtailment rate of 3 percent.

Table 1. Components of Each Scenario and Summaries of Scenario Analysis Results (2034)

Scenario	Components of Scenario					Scenario Analysis Results (2034)				
	Solar and wind generation capacity (MW)		Cumulative storage system capacity (MW; 2034)		Synchronous condensers	Power plant utilization rate			Curtailment rate	Total system cost (TSC) *2022-2034 TNPV (cost-benefit vs. As-Is) (KRW)
	2022	2034	Battery energy storage system	Hydrogen storage system		Traditional power supply equipment (LNG, heavy oil, HVDC transmission) (Utilization rate compared to 2022)	Solar	Wind		
As-Is	1,031	3,982	0	0	No	25.6% (▼13.4%)	10.1%	19.4%	19.2%	3.5Tn
CFI 2030	1,634	3,982	678	1,525	No	23.0% (▼ 16.0%)	13.2%	24.2%	3.0%	6.4Tn (▲ 2.9Tn)
			614	536	Yes	20.1% (▼ 18.9%)	13.2%	24.2%		3.7Tn (▲ 0.2Tn)

Second, with an investment of just 5.7 percent (KRW 0.2 trillion) in addition to the status quo (the "As-Is Scenario") of the cumulative total system cost by 2034, it is possible to adhere to the CFI 2030 plan, while still keeping the renewable curtailment rate at a low three percent. The cumulative total system cost** under the As-Is Scenario (under which the renewable curtailment rate is expected to reach 19.2 percent) is estimated to reach about KRW 3.5 trillion by 2034. Our analysis suggests that, if an additional investment of 5.7 percent of that cumulative total system cost is used to install synchronous condensers and storage systems, the CFI 2030 goal can be realised while maintaining the curtailment rate at 3 percent.

* 2022-2034 total net present value (TNPV)

**Such social costs as fuel costs (e.g., heavy oil and LNG) and carbon costs are included. For carbon costs, the Korean references set by the Network for Greening the Financial System (NGFS), a global network of central banks and supervisory authorities advocating a greener financial system, are applied

Third, installing more flexibility resources, such as storage systems and synchronous condensers under the CFI 2030 scenario, will bring down the utilization rate of the existing power supply facilities owned by KEPCO's subsidiaries (including oil and LNG) as much as 19 percentage points by 2034, when compared to 2022. More flexibility resources like storage systems and synchronous condensers will contribute to more renewable energy facilities being utilized. Simultaneously, the utilization rate of the existing power supply facilities (fossil fuel-based plants owned by KEPCO's subsidiaries and incoming HVDC transmission) will fall to a 20-percent level by 2034, a maximum drop of 19-percentage points compared to 2022.

This report confirms the existence of technical scenarios that are economically reasonable and also could address the issue of excessive curtailment without slowing the grid penetration of renewables. We found that, under the CFI 2030 scenario, the more flexible a power grid is, the utilization rate of renewable energy generators goes up, while that of traditional power sources (LNG, oil, and incoming HVDC transmission) goes down. Such a decline in the reliance on traditional power sources would pose a financial risk to KEPCO and its generation subsidiaries, which own most of the fossil fuel-based power plants on the island.

At the same time, KEPCO and its generation subsidiaries may exert a significant level of influence on grid access and compensation, as they retain substantial voting rights on the KPX Electricity Market Operation Committee, the KPX board of directors, and the general assembly of KPX members. Therefore, it is imperative that KPX's decision-making process becomes more independent, which requires not only reform of KPX's governance, but also implementation of measures to reduce KEPCO's overall influence on the power market, such as severing financial ties between KEPCO's power generation and power grid businesses. Only when these measures are in place will KPX be able to actively and fairly increase the integration of renewable energy and flexibility resources.

In consideration of the scenarios considered in this report, we present the following policy recommendations:

First, the Korean government should be more proactive in devising measures to improve the power market and the grid systems.

Second, the government should formulate a fair compensation scheme to promote a more expansive use of such flexibility resources as storage systems and synchronous condensers, thereby minimizing renewable generation curtailment.

Third, the government should prevent fossil fuel generators from receiving excessive compensation benefits denied to their renewable counterparts by improving the cost-plus mark-up guarantee scheme and limiting the volume and eligibility criteria of the Capacity Payment (CP) for fossil-fuel-based generators.

Envisioning a Step Further

To devise a more cost-efficient solution for the renewable curtailment issue, the ideal situation would result in measures to strengthen the demand-side flexibility, such as Demand Response (DR) and sector coupling (inter-sectoral integration). However, this report only considers the introduction of technologies that could compensate for the volatility of variable renewable energy (VRE), like solar and wind energy, and doesn't address the key demand-side measures like Plus DR or sector coupling. The reason for this is to ease the complexity of the optimal investment decision processes and derive more intuitive scenarios. We believe that the CFI 2030 goals can be achieved at a cost even lower than that suggested in this report, should demand-side flexibility be given a bigger significance in the future.

The scenarios outlined in this report consider HVDC, which connects Jeju Island's power grid to mainland Korea. The transmission of power from the mainland to Jeju via HVDC tie-lines ("inbound" HVDC transmission) does not distinguish energy based on its generation source – it includes power from renewables and fossil fuels, among others. There are differing opinions, therefore, on whether it is rational to reflect HVDC capacity in Jeju's energy plan to become a carbon-free island. This report suggests a heavier use of "outbound" HVDC transmission (from Jeju to the mainland) as a means to respond to the excess power generation issue on the island.

Solutions for Our Climate (SFOC) and NEXT Group have ascertained through this study that there are cost-efficient technical solutions to Jeju's curtailment issues. This report sets the foundation for future research about the mainland grids, on which curtailment issues are also expected to proliferate. This future study of mainland grids will also factor in the methods to flexibly manage the demand through various mechanisms.

02

Background

2-1. Carbon-Free Jeju is a prequel to Korea’s energy transition

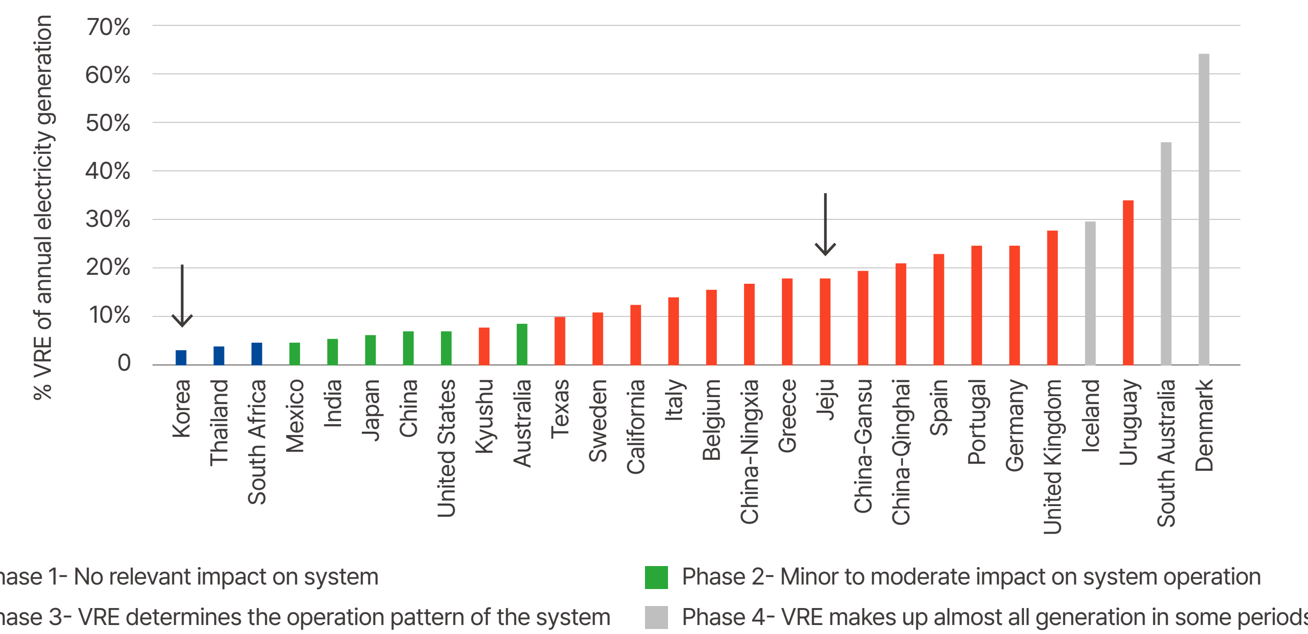
In 2015, Jeju began to curtail renewable energy (it should be noted that the term 'curtailment' in this report refers only to that of renewable energy generation and not to any other types of curtailment). The frequency of curtailment orders has risen sharply year after year to reach 64 in 2021. Almost 60 curtailment orders have been issued in Jeju in the first half of 2022, possibly hinting a record-high year.[6] Considering that the island’s renewable generation capacity is projected to triple or even quadruple between 2020 and 2030,[7] continued reliance on curtailment to tackle the overgeneration of power cannot be sustainable nor is it compatible with the higher goal of achieving carbon neutrality.

It is becoming ever more important to tackle Jeju’s renewable energy curtailment issue because growing volatility and excess generation will expand to be a nationwide problem as renewables take up a bigger portion in the energy mix. According to the phases of VRE integration set forth by the International Energy Agency (IEA),[8] Korea’s nationwide VRE generation share only accounts for 3 percent of the total power generation (Phase 1).[9] But taking Jeju aside, the island has already reached Phase 3 with 18% of VRE generation share, which indicates it should start responding to flexibility issues like power volatility and oversupply.[10] Renewable energy curtailment Jeju is facing is destined to eventually impact the other parts of Korea. In fact, Sinan, a county in South Jeolla Province is facing the same issue due to increased solar generation,[11] which is poised to expand to the other power grids of the country.

6 KPX (2022). “Monthly New & Renewable Energy Generation Curtailment on Jeju Island (Wind)” at https://www.data.go.kr/data/15100208/fileData.do.
7 KIM Yeong-hwan (Aug. 26, 2022) “Ways to build an adequate renewables acceptance system to boost distributed energy resources (DER)” [presentation at a conference] A Seminar on How to Boost DER by Reducing Curtailment. Seoul, ROK. http://www.yangyi.kr/assembly_post/3291
8 IEA (2017). “Getting Wind and Solar onto the Grid” at https://www.iea.org/reports/getting-wind-and-solar-onto-the-grid
9 New and Renewable Energy Center under the Korea Energy Agency (2022). “2020 New and Renewable Energy Statistics” at https://www.knrec.or.kr/biz/pds/statistic/view.do?no=120
10 KIM Yeong-hwan (Apr. 28, 2022) “Implications of Excess Renewable Energy Generation on Jeju Island” [presentation at a conference] Direction for Power Market System Improvements for Net Zero by 2050 by the Incoming Government: A Renewable Energy Curtailment Seminar. Seoul, ROK
11 JEONG Hyeong-seok (2021) “Solar Curtailment Began Even in Non-Jeju Region” at https://www.electimes.com/news/articleView.html?idxno=214432 accessed on Sept. 6, 2022

Figure 1. IEA Variable Renewable Energy Grid Integration Phase

<Annual VRW Share and Corresponding System Integration Phase in Selected Countries/Regions, 2018>



Source: IEA (2019) “Status of Power Grid Transformation 2019”
Redesigned by SFOC

The issue of curtailment is not a surprise but rather a naturally expected consequence following the expansion of renewables, but it could act as a drag on the growth of renewables if the country fails to establish a fundamental solution. The third Energy Master Plan announced in 2019 aims to increase the percentage of renewables in power generation to 35 percent by 2040. It has been pointed out that curtailment, as well as a shortage of backup infrastructure (e.g., energy storage systems and gas turbine generators) to address curtailment, prevented the master plan from targeting a higher percentage.[12]

12 Ministry of Trade, Industry and Energy (2019) “The Third Energy Master Plan”

Table 2. Estimated Curtailment Rates for Scenarios with Different Generation Shares under the Third Energy Master Plan

Generation Share in 2040	25%	30%	35%	40%
Curtailment Rate (yearly)	1.0%	4.4%	11.0%	21.5%

Also, the recently announced working-level proposal for the tenth Electricity Supply and Demand Master Plan has greatly reduced the renewable generation share target against the 2030 NDC from 30% to 21.5%, quoting the community acceptance and 'feasibility' as reasons for the downscale.[13] The 'feasibility' reason raised here implies that 'the current power grid does not have enough flexibility resources to accommodate the increasing renewable power, which also means the curtailment issue is yet to be resolved.' In conclusion, finding a solution to the curtailment issue is a decisive factor in promoting the expansion of renewable energy use.

As such, getting to grips with Jeju's renewable generation curtailment issue will help contribute to the expansion of renewables, act as a yardstick to determine the success of Korea's energy transition, as well as significantly impact the country's achievement of the 2030 NDC and 2050 carbon neutrality targets. Clearly, the island should urgently address the curtailment issue – which will become both the starting point and a necessary prequel to Korea's pathway toward achieving net zero.

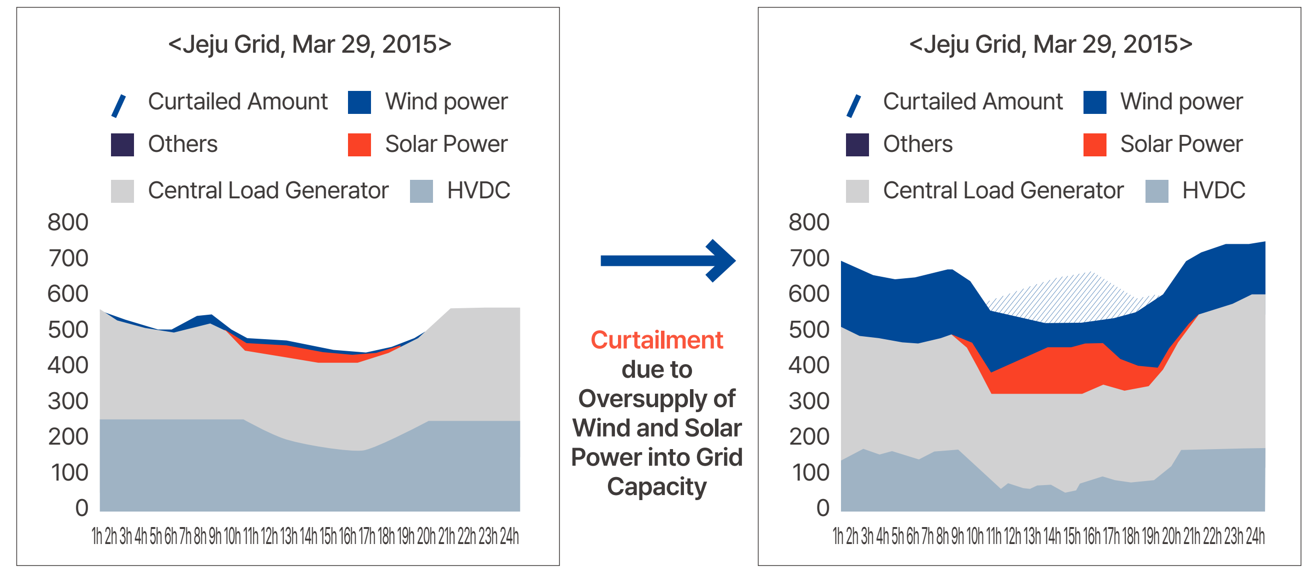
13 Ministry of Trade, Industry and Energy (2022) Working-level proposal for the tenth Power Supply Master Plan by the relevant sectional steering committee

2-2. What is Curtailment?

Stable operation of the power grid is often likened to bike riding.[14] When riding a bicycle, the forces that spin the right and left pedals must be kept in balance in order for the bike to gain inertia and run stably. Likewise, operating power grids require 1) balance between power supply and demand and 2) maintaining grid stability as the most critical factors.

Figure 2. Illustration of the cause of renewable curtailment

[Renewable Curtailment in Jeju Island]



Source: Jeju Grid, Mar 29, 2015

Curtailment aims to maintain those two requirements: supply-demand balance and grid stability. Just like bike pedals, the power grid should maintain a stable frequency of 60Hz and a constant voltage at any given time by keeping the balance between supply and demand. In case there is a misalignment or imbalance between supply and demand, or if a sudden surge in supply causes a large change in output, throwing the grid's frequency and voltage into instability, the grid could become unstable and lead to accidents like large-scale blackouts.

14 IEA (2017) "Getting Wind and Solar onto the Grid" at https://www.iea.org/reports/getting-wind-and-solar-onto-the-grid

The output of VREs like solar and wind innately fluctuates by natural conditions such as the available sunlight and wind, leading to a significant volatility in supply. Large and inflexible traditional power grids that heavily depend on large-scaled baseload power generators find it challenging to flexibly regulate their outputs and quick response to the volatile VREs may be difficult. In particular, if a system is not flexible enough to address an upsurge in VRE supply in hours when power demand is relatively low (which endangers supply-demand balance) or an increase in output volatility (which compromises system stability), VRE curtailment may be an unavoidable option.

Moreover, a supply-demand imbalance may occur during off-peak hours when power demand is low or during the daytime when both solar and wind power is generated, making the duck curve[15] far more pronounced and therefore precipitating more events of curtailment. To rectify the timing imbalance, a departure from the inflexible traditional way of operating power grids is inevitable; to migrate toward a VRE-driven power grid, a flexible power grid operations management mechanism is essential.

A more flexible power grid will enable both VRE expansion and curtailment minimization by effectively responding to a wider range of VRE-related timescale volatility—from short- to long-term—, thereby affording a stable supply of power. Jeju has been moving slowly in adding flexibility to its power grid while quickening its pace in embracing renewables, and this misalignment has resulted in unbridled VRE curtailment.

2-3. Overseas Cases of Curtailment – Denmark, Germany, and the UK

It now comes to this question: How do countries with far higher shares of renewables handle curtailment? Let us take, for example, Denmark (which is at Phase Four, the highest of the IEA's VRE integration phases), Germany (Phase Three), and the UK (Phase Three) to compare their curtailment issues and corresponding responses.

The share of wind power generation in the three countries, which boast world-class VRE integration rates, exceeds 47 percent, 24 percent, and 21 percent, respectively, but their average curtailment rates are kept at 3.69 percent.[16] As seen in Table 3 below, renewables are common in Europe, and the three countries are in the vanguard of the battle against wind power curtailment. The below is a summary of their curtailment situations and response measures.

15 The duck curve illustrates a phenomenon in which demand for non-renewable energy declines or climbs as power generation from such renewable sources as wind or solar increases or decreases along the course of the day or depending on the weather. In other words, demand for non-solar energy remains low between sunrise and sunset (during which solar power generation peaks) but surges after sunset. The graph looks like a duck; hence the name, duck curve. (Source: Naver Knowledge Encyclopedia)

16 Yasuda et al.(2022)

Table 3. Wind Power Shares and Curtailment Rates & Responses of Three European Wind Power Leaders[17]

		Denmark	Germany	UK
IEA Integration Phase		Phase Four (23% or higher)	Phase Three (13-23%)	Phase Three (13-23%)
Wind Power Share (2019)[18]		47.2 %	24.2 %	21.3 %
Curtailment Rate (2019)[19]		3.31 %	4.83 %	2.93 %
Characteristics		- VRE (including wind) accounts for 58% of power generation. - Power grids interconnected with neighboring countries account for 50% of the total capacity.[20]	- 70% of wind power is generated in the north. - Main reason for curtailment: Constraints on power transmission between the north and the south, which has greater demand for power	- 44% of the total offshore wind power in Europe in 2019 - Main reason for curtailment: Surplus wind power in Scotland
Key Response Measures	Policy Support	- Enactment of the Promotion of Renewable Energy Act in 2009 - Government-led support for wind power - Comprehensive plans for VRE development and more transmission cables	Enactment of the Energy Line Expansion Act (EnLAG, 2009) and the Grid Expansion Acceleration Act (NABEG, 2019), which are intended to boost new line constructions for greater grid interconnectedness with other countries.[21]	'Stability Pathfinder' program aimed at improving system stability by NGESO, a system operator
	Improvement of Power Markets and Power Grids	- Improve the power market to increase system flexibility and VRE generation - Introduction of a next-generation grid operation mechanism	- Expansion of the domestic power grid, as well as of power grids with neighboring countries - Priority on renewable energy in purchasing and grid connectedness - Shares of costs of compensating for curtailment and securing reserves in the grid stability costs are rising.	- Surplus power is sold to Northern Island through the subsea cables connecting Northern UK to Northern Ireland - Level of curtailment compensation is determined by in-market bidding

Source: Information obtained from the sources in the footnotes and reorganized by the SFOC.

The share of wind power and the key causes for curtailment in the three countries vary depending on their geographical traits and power grid status. However, there are two common features broadly seen across their response measures: **policy support** (e.g., enactment of conducive laws providing for a range of support measures) and **the improvement of power markets and power grids** (e.g., establishment of a compensation system and a power grid operation mechanism that incentivize VRE expansion). With such an approach, the countries are effectively expanding the penetration of renewables while minimizing curtailment, which generally tends to increase if VREs grow.

17 KIM Nam-il, LEE Seong-gyu (2021) "Analysis of Association Between VRE Increases in European Countries and International Power Trade: Implications for Northeast Asia"; Korea Energy Economics Institute (2018) "Research on How to Improve the Power Market System for Shift to Low-Carbon Power Grids," AHN Jae-gyun

18 Yasuda et al.(2022)

19 Yasuda et al.(2022)

20 KIM Yeong-hwan (Apr. 28, 2022) "Implications of Excess Renewable Energy Generation on Jeju Island" [presentation at a conference] Direction for Power Market System Improvements for Net Zero by 2050 by the Incoming Government: A Renewable Energy Curtailment Seminar. Seoul, ROK

21 LEE Sang-ho (Aug. 4, 2021) "Issues and Status of German Power Transmission Industry," Journal of the Electrical World at http://www.keaj.kr/news/articleView.html?idxno=4219 accessed on Sept. 6, 2022

2-4. Why is Curtailment an Issue in Korea? – Renewable Energy Targets Are Downscaled, the Destination of Net Zero Is Farther away

In contrast, Jeju's power grid still appreciably depends on must-run generators fired by heavy oil or LNG and incoming power from the mainland by HVDC transmission, which also mostly comprises of fossil-fuel-based power. In 2021, there was a policy support for Jeju – a legislative attempt to reduce curtailment on the island. A bill for a special act to promote distributed energy, which contains a provision for designation of Jeju as a special zone for distributed energy,[22] was proposed[23], but there since has been little progress. The government is also considering pilot projects to introduce real-time and ancillary services markets and a low-carbon, centralized contract market for energy storage systems (ESS) to shore up the island's system flexibility.[24] These efforts to improve the power market mechanism and power grids,[25] however, have been carried out at a sluggish pace in contrast to the swift penetration of renewables on the island of Jeju. As a result, VRE curtailment has been on a non-stop rise.

Some even predict that in 2034, roughly 39 percent of new and renewable energy generation of Jeju will face curtailment, a total of half the year,[26] and that the same year will see 326 solar or wind power curtailments.

In the midst of such gloomy forecasts, Jeju has even started to decelerate the expansion of renewables in response to curtailment. Since around the end of 2021, the island has been fiddling with the idea of a capacity cap on new and renewable energy ("NRE capacity cap") in an effort to slow down the expansion of renewable energy[27] (see Table 4). This policy judgment stems from the perception that at the heart of Jeju's curtailment issues lie excessively rapid growth and overproduction of renewable energy.

While it is clear that VREs will continue to expand in Jeju, the current responses (expanding curtailment without providing proper compensation for renewable energy producers and downscaling renewable targets) cannot become a substantial resolution for the following reasons:

22 KIM Byeong-uk (Jul. 27, 2021) "Pursuit of Energy Decentralization Via Distributed Energy Zone," Today Energy at http://www.todayenergy.kr/news/articleView.html?idxno=238740 accessed on Sept. 6, 2022
23 PARK Yun-seok (Ju. 28, 2021) "Legal Grounds for Energy Decentralization," Electric Power Journal at http://www.epj.co.kr/news/articleView.html?idxno=28393 accessed on Sept. 6, 2022
24 YUN Dae-won (Aug. 30, 2022) "Contract Market Pursued as Solution to Low Economic Feasiblity of ESS," The Electric Times at https://www.electimes.com/news/articleView.html?idxno=308177 accessed on Sept. 6, 2022
25 LEE Sang-bok (May 2, 2022) "Realtime & Ancillary Services Markets Are to Open," Energy and Environment News at https://www.e2news.com/news/articleView.html?idxno=241430 accessed on Sept. 7, 2022
26 LEE Tae-yun (Oct. 12, 2021) "Six Months of Jeju Renewable Curtailment Expected for 2034," Halla Daily News at http://www.ihalla.com/read.php3?aid=1634018187714937010 accessed on Sept. 6, 2022
27 GANG Seung-nam (Sept. 9, 2022) "Frequent Wind/Solar Curtailment on Jeju ... Solutions Prove Elusive," News1 at https://www.news1.kr/articles/?4767641 accessed on Sept. 6, 2022

First, a heavier dependence on curtailment would erode the profitability of renewable energy producers and increase uncertainty in prediction, making it difficult to raise finance. **Second,** the development and introduction of technologies for power grid flexibility, required for greater integration of renewables, would be less incentivized, hampering the creation of a renewable ecosystem. As a consequence, the potential to incorporate more renewable energy into the power grid would be undermined and the CFI 2030 and 2050 net zero journeys would become bumpier.

The volatility of VREs, given their nature, entails some degree of curtailment for grid stability, but efforts must be made to grow the share of renewables while keeping curtailment below a certain level by means of a range of technical measures, as well as through institutional improvements for funding and policy support.

Table 4. NRE Capacity Cap, CFI 2030 Plan, and Ninth Electricity Supply and Demand Master Plan

[Capacity Cap on New and Renewable Energy (NRE Capacity Cap)]

According to the Jeju Research Institute, which conducted "A Study on Power Grid Stabilization and Optimum Renewable Scale for Jeju," aimed at launching an NRE capacity cap,[28] the island will, with an NRE capacity cap, slow down solar expansion in 2022-2023 and decelerate wind growth in 2025-2026 before it gets back on track in 2026 to keep abreast of the original CFI 2030 Plan and the ninth Electricity Supply and Demand Master Plan. A news report states that in 2021, Jeju planned to apply an NRE capacity cap starting in the first half of 2022.[29]

[CFI 2030 Plan]

In 2012, Jeju declared the CFI 2020 Plan and announced additional net zero policies, including utilizing new and renewable energy to cover 100% of the island's power demand and replacing all of its cars with EVs. The key is to increase the combined capacity of wind and solar power from 1,821 MW in 2022 to 4,085 MW in 2030. Since the announcement of the CFI 2030 Plan, Jeju's wind and solar farms grew rapidly to account for 18 percent of the island's total power generation in 2020.[30] The strong drive toward renewables has made Jeju a testbed for energy transition for the rest of Korea.

[Ninth Electricity Supply and Demand Master Plan]

The CFI 2030 Plan was incorporated into the ninth Electricity Supply and Demand Master Plan, a national renewable energy supply plan.[31] The latter's renewable capacity targets are higher than those of the former.

28 LEE Eun-ji (2021) "Jeju Slackens NRE Drive and Is to Introduce NRE Cap Next Year," Jemin Daily at http://www.jemin.com/news/articleViewAmp.html?idxno=728855 accessed Sept. 6, 2022
29 LEE Eun-ji (2021) "Jeju Slackens NRE Drive and Is to Introduce NRE Cap Next Year," Jemin Daily at http://www.jemin.com/news/articleViewAmp.html?idxno=728855 accessed Sept. 6, 2022
30 KIM Yeong-hwan, "Implications of Excess Renewable Energy Generation on Jeju Island" [presentation at a conference], Direction of Power Market System Improvements for Net Zero by 2050 by the Incoming Government: A Renewable Energy Curtailment Seminar. Seoul, ROK
31 Power Supply Master Plans are biennially formulated in accordance with Article 25 of the Electric Utility Act and represent Korea's comprehensive electric power policy encompassing the basic direction, long-term forecasts, facility plans, power demand management, and more. The ninth Power Supply Master Plan for 2020-2034 is the latest one (as of September 2022). A working-level proposal for the tenth was recently announced, and a strategic environmental impact assessment and inter-ministerial consultation for it are being conducted. The Electric Policy Council will finalize the plan through deliberation.

Table 5. Comparison of New and Renewable Energy Targets of Different Policies (Unit: MW)

Year	Ninth Electricity Supply and Demand Master Plan[32] (CFI 2030 Plan Reflected)	NRE Capacity Cap[33]
2022	1,634	1,031
2025	2,299	2,299
2030	3,756	3,756
Energy Sources	Solar and wind	Solar and wind

In consideration of the policy background for the reflection the CFI 2030 Plan in the ninth Electricity Supply and Demand Master Plan and for the sake of convenience, this report dubs the scenarios meeting the renewable targets of the ninth Electricity Supply and Demand Master Plan (which incorporates the CFI 2030 Plan) **CFI 2030 Scenarios.**

On the other hand, this study refers to a scenario that pursues the targets of the NRE capacity cap as an **As-Is Scenario** because Jeju is expected to stop putting brakes on the expansion of renewables by means of the NRE capacity cap, unless it seeks any active solutions to Jeju's curtailment issues.

Noting that renewable expansion leads to increasing curtailment, which in turn results in deceleration of renewable penetration (which is the current response), this report attempts to explore technical solutions to the situation. This study focuses on Jeju (which is mired in curtailment before the other parts of Korea) and attempts to build the most cost-efficient scenarios possible to handle curtailment and draw policy suggestions therefrom.

32 Ministry of Trade, Industry and Energy (2020) "Ninth Power Supply Master Plan"
33 GANG Seung-nam (2021) "Jeju Considers Yearly Capacity Cap to Tight Rein on Wind and Solar," News1 at https://www.news1.kr/articles/?4524241 accessed on Sept. 7, 2022

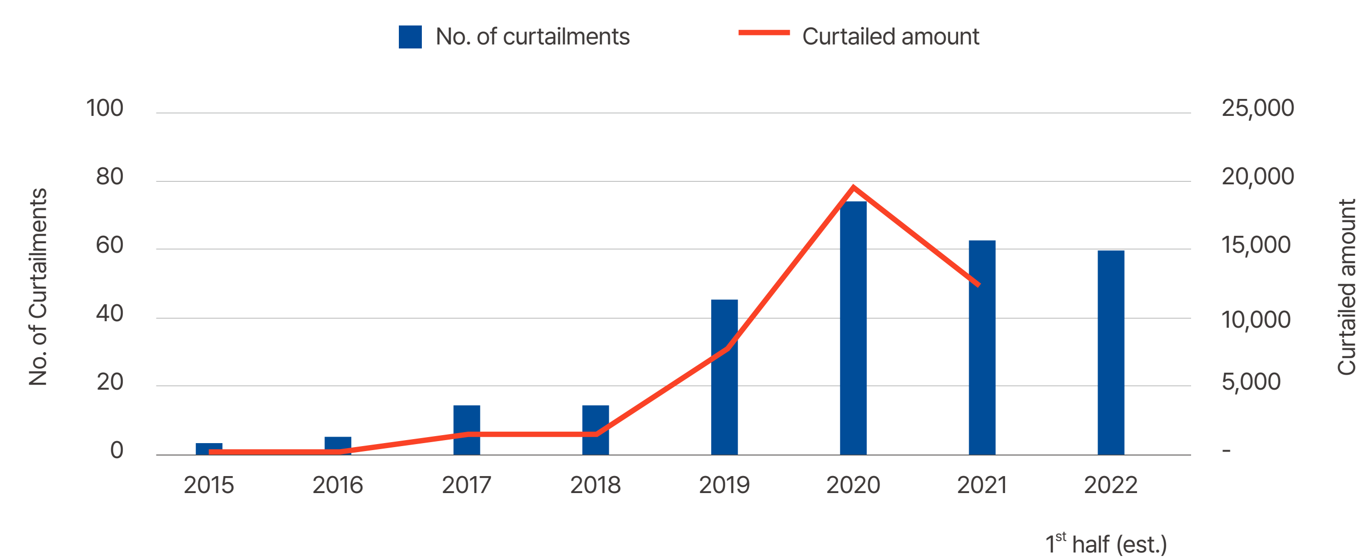
03

3. Curtailment on Jeju Island: Status and Causes

3-1. Status of Curtailment on Jeju

Jeju took three renewable curtailment orders in 2015, followed by 77 in 2020,[34] 64 in 2021,[35] and about 60 in the first half of 2022, presaging a new yearly high.[36] The island's curtailment rate[37] rose from 0.04 percent in 2015 to 2.09 percent in 2021, and the total curtailed amount 12,016 MWh in 2021. A loss of KRW 3 billion has been incurred in 2020 due to curtailment in wind power alone.[38] Curtailment orders, which had been confined to wind power, began to spill into solar starting from 2020.

Figure 3. Jeju's Wind Curtailment Trend



Source: KPX, "Monthly New & Renewable Energy Generation Curtailment on Jeju Island (Wind)"
Reorganized by SFOC

34 KPX (2022), "Monthly New & Renewable Energy Generation Curtailment on Jeju Island (Wind)" at https://www.data.go.kr/data/15100208/fileData.do.
35 KPX (2022), "Monthly New & Renewable Energy Generation Curtailment on Jeju Island (Wind)" at https://www.data.go.kr/data/15100208/fileData.do.
36 KPX (2022), "Monthly New & Renewable Energy Generation Curtailment on Jeju Island (Wind)" at https://www.data.go.kr/data/15100208/fileData.do.
37 KIM Yeong-hwan (Aug. 26, 2022) "Ways to build an adequate renewables acceptance system to boost distributed energy resources (DER)" [presentation at a conference] A Seminar on How to Boost DER by Reducing Curtailment. Seoul, ROK.
38 GANG Seung-nam (Sept. 9, 2022) "Frequent Wind/Solar Curtailment on Jeju … Solutions Prove Elusive," News1 at https://m.news1.kr/articles/?4767641#_enliple accessed on Sept. 6, 2022

3-2. Root Causes of Jeju's Curtailment—with Focus on the Characteristics of the Island's Power Grid

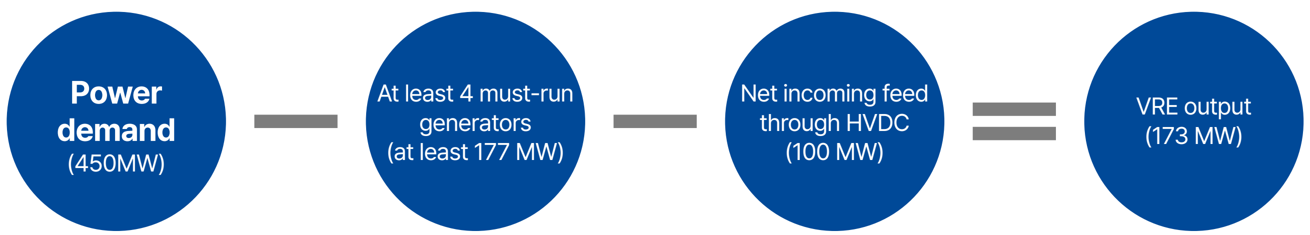
The rise in curtailment on Jeju is due to excess power generation compared to demand. The obstacles to resolving excess power generation include the following traits of the island's power grid:

① Inflexible power grid operation – Sunshine, Winds, and Must-Run Generators

Success in resolving Jeju's curtailment issues depends on how well the island will render its power grid more flexible to integrate VRE generation. In order to more generously embrace VREs (which inevitably entails volatility), the power grid needs have greater flexibility to enable VRE-oriented management of power loads.

However, when the power grid of the island, determines the acceptable level of VRE, only after considering the capacities of the must-run generators and the HVDC cables together with power demand does the island take into account the capacities of the remaining facilities (see Figure 4). That is, the island runs its power grid in a rigid manner by applying the capacities of its must-run generators and HVDC cables as constants, while it really should be seeking ways to flexibly operate the grid to increase renewable generation with its increasingly common renewable facilities.

Figure 4. Jeju Power Grid's Formula to Determine VRE Output

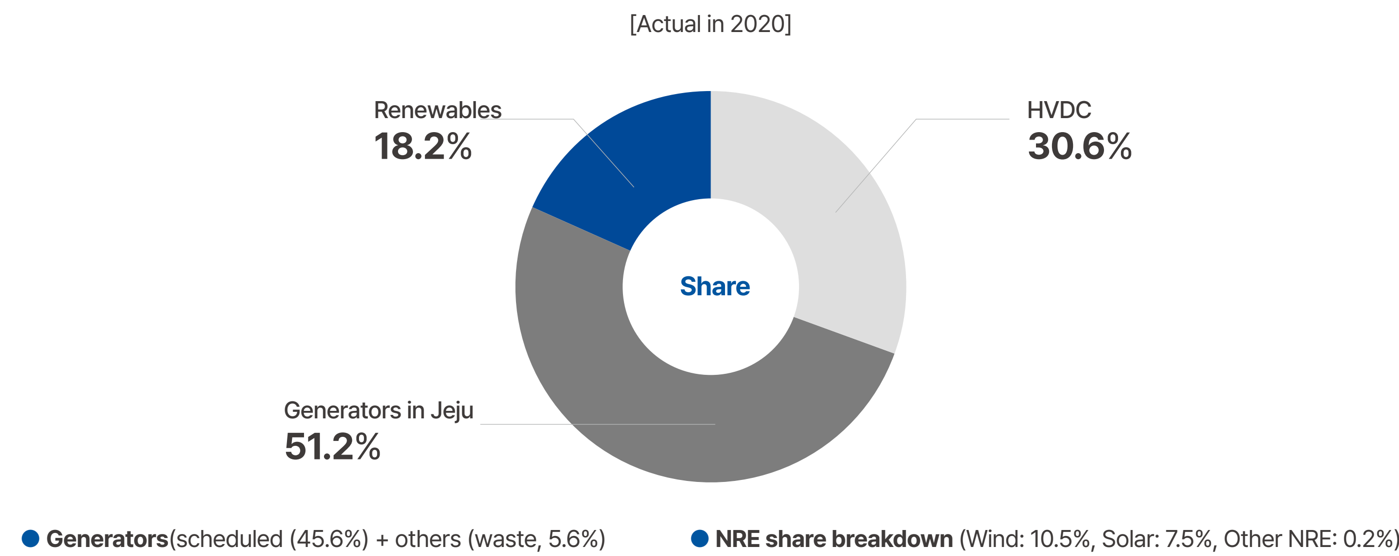


Source: KPX (2021)
Reorganized by SFOC

In 2020, must-run generators and HVDC represented 81.8 percent of Jeju's power.[39] Flexible operation of the power grid requires minimization of the criteria for the use of must-run generators and the incoming HVDC transmission and crafting of solutions for greater integration of VRE into the grid.

39 KIM Yeong-hwan (Apr. 28, 2022) "Implications of Excess Renewable Energy Generation on Jeju Island" [presentation at a conference] Direction for Power Market System Improvements for Net Zero by 2050 by the Incoming Government: A Renewable Energy Curtailment Seminar. Seoul, ROK

Figure 5. Shares of Different Energy Sources on Jeju



Source: Jeju KPX (2020)

In addition, excessive power generation, coupled with an absence of large-scale industrial facilities, limits Jeju's efforts to push up power demand itself. That is why the island also needs to endeavor to increase the flexibility of power demand through such flexibility resources as demand response (DR) and sector coupling (integration of different sectors)

This report, however, considers only the introduction of technologies to counter the volatility of VREs in order to alleviate the complexity surrounding optimal investment decision making and derive intuitive scenarios. It should be noted that it sets aside other feasible solutions to volatility such as demand response and sector coupling, which are hotly debated for demand side management.

(Fossil fuel-fired must-run generators)

When KPX determined the minimum required number of, and the minimum output standards for, fossil-fuel-based generators for Jeju, the Korean electricity market considered only the island's must-run generators, which must be run in order to maintain system inertia and reliability (see Table 6). This means that a certain level of power output is guaranteed for Jeju's must-run generators that run on heavy oil or LNG. In 2020, heavy oil- or LNG-fired generators reached almost 51.2 percent of power generation.[40]

40 KIM Yeong-hwan (Apr. 28, 2022) "Implications of Excess Renewable Energy Generation on Jeju Island" [presentation at a conference] Direction for Power Market System Improvements for Net Zero by 2050 by the Incoming Government: A Renewable Energy Curtailment Seminar. Seoul, ROK

Should there be a way to reduce the share of must-run generators while maintaining grid reliability, the island can accommodate more renewable capacities while reducing the curtailment in renewables.

Table 6. Minimum Required Number of Generators for Operation for Different Loads[41]

Load	Minimum Number of Generators Required to Operate
500 or below (MW)	4
501 – 600 (MW)	5
601 – 900 (MW)	6
901 or higher (MW)	7

(HVDC cables connecting Jeju to the mainland)

Jeju's power grid is not synchronized with the power grids outside of Jeju, so HVDC transmission has been sending power from mainland Korea to Jeju. In 2020, power fed into Jeju via HVDC transmission represented 30.6 percent of the island's total power supply.[42] However, Jeju receiving fossil fuel-sourced power from the mainland via HVDC transmission may not align with the purpose of the CFI 2030 Plan.

On the other hand, it is expected that Jeju will see oversupply of renewables increase as is the need for outgoing HVDC transmission (which feeds out Jeju's surplus power to the mainland through HVDC transmission). HVDC Tie-Line 1 and 2, which are currently in commercial operation, possess technical limitations for outbound transmission because they were originally designed for inbound purposes. A technical review is underway to determine the possible outbound HVDC transmission capacity for a stable transmission of power from Jeju to the mainland. Meanwhile, construction of HVDC Tie-Line 3 is underway for outbound transmission. Once complete, there will be an added outbound transmission capacity of 150MW from 2024.[43] As the island becomes able to send out more electricity, the occurrences and amount of curtailment will decrease greatly.

41 Jeju Energy Agency, Jeju Special Self-Governing Province (2021) "Jeju's Renewable Generation Curtailment and Ways to Reduce it"
42 KIM Yeong-hwan, "Implications of Excess Renewable Energy Generation on Jeju Island" [presentation at a conference], Direction of Power Market System Improvements for Net Zero by 2050 by the Incoming Government: A Renewable Energy Curtailment Seminar. Seoul, ROK
43 The Korea Electric News (Apr. 18, 2022) "Groundbreaking for HVDC Tie-Line 3 Tying Eastern Jeju to Wando Island," The Korea Electric Power News at https://www.epnews.co.kr/news/articleView.html?idxno=61238.

Nevertheless, in addition to outbound power transmission, there should be a fundamental resolution that would internally rectify Jeju's curtailment issues within its power grid. There are already concerns that sending renewable energy from Jeju out to the southwest coast of the country (South and North Jeolla Provinces), where a number of renewable energy generators are being constructed, will eventually threaten grid stability in those regions.[44]

Table 7. Jeju's HVDC Transmission System[45]

Tie Lines	HVDC Tie-Line 1	HVDC Tie-Line 2	HVDC Tie-Line 3
Route	Jeju – Haenam CS	West Jeju – Jindo C/S	East Jeju - Wando
Converter	Current source converter (GE)	Current source converter (GE)	Voltage source converter (ABB)
Cable	96 km (Alcatel)	105 km (LS Cable & System)	89 km (LS Cable & System)
Capacity	150MW×2P, DC±180kV	200MW×2P, DC±250kV	200MW×1P, DC±150kV
Milestones	Contract execution: Oct. 1991 Start of operation: Mar. 1998	Contract execution: Feb. 2009 Start of operation: Apr. 2014	Groundbreaking: Apr. 2022

② Unfair Compensation Scheme– Traditional power supply facilities with focus on fossil-fuel-based generation vs. new and flexibility resources

To minimize the use of must-run generators and HVDC and expand the use of renewables, it is pivotal to utilize flexibility resources that compensate for the volatility of VRE and contribute to system stability. Key technologies adding flexibility to power grids include energy storage systems (ESS), which store oversupply of renewable energy, and synchronous condensers, which help maintain system reliability by giving inertia to power grids even without power generation.

44 LEE Hun (Jul. 8, 2021) "How to Stabilize Jeju's Power Grid," Journal of the Electrical World at http://www.keaj.kr/news/articleView.html?idxno=4135 accessed on Sept. 7, 2022
45 YUN Yeong-jin, JO Seong-bin, KIM Yeong-hwan (2021) "A Study on Scenarios for Outgoing Power Transmission from Jeju Through HVDC Tie-Lines 1, 2, and 3," Proceedings of the 2021 Summer Conference of the Korean Institute of Electrical Engineers

The expansion of VRE comes with an inevitable shortcoming: excess VRE, generated by more abundant sunshine or winds than needed, cannot be stored but must be jettisoned by means of, for example, curtailment. Energy storage systems can fix the issue. While they are charged and discharged repeatedly as renewable energy generation varies, there is a way to utilize any surplus power. However, since ESSs come with a high installation cost, it is critical to determine the right storage capacity to build. In particular, battery energy storage systems (BESS), which are widely used for power grids, have a disadvantage of high cost of batteries, which determine the storage capacity of the battery energy storage systems. As an alternative, hydrogen storage systems may also be considered.[46] The capacity of hydrogen storage systems is proportional to the capacity of their hydrogen tanks, which are relatively inexpensive, so they are appropriate for storing larger amounts of energy.

A synchronous condenser is a resource that rotates in synchronization with the frequency of the power grid concerned. While synchronous condensers do not produce power by themselves, they are capable of providing reactive power and system inertia. Installation of synchronous condensers will reduce the number of must-run generators to operate, thereby cutting down the curtailment of renewables.

Unfortunately, various flexibility resources, including energy storage systems, synchronous condensers, and demand response, are not adequately fulfilling their capabilities. Despite their capability to augment grid flexibility, their biggest hindrance to market entrance is the lack of economic profitability.

It is difficult to even recover the investment cost for ESSs in the current power market structure, let alone garner profit from after their costly installation. The resultant delay in introduction of flexibility resources has left Jeju with one option to deal with surplus power: VRE curtailment.

Against this backdrop, this report analyzes scenarios that put priority on VRE expansion coupled with introduction of flexibility resources and analyzes the costs for each scenario.

46 Among the long-duration energy storage systems, a hydrogen storage system comprising a water hydrolysis unit, a hydrogen tank, and a fuel cell unit is particularly noteworthy. Hydrogen tanks, which determine the energy storage capacity of hydrogen storage systems, are cheaper than batteries, so they are suitable for long-duration energy storage systems. With a hydrogen storage system, excess power during off-peak hours is fed to the hydrolysis unit to produce hydrogen, which is then stored in the hydrogen tank, and during peak hours, the stored hydrogen and the fuel cell unit are used to produce power.

04

4. Composition and Cost Analysis of Technical Scenarios Minimizing Jeju's Curtailment

4-1. Methodology: Overview

Jeju's renewable plans to date have been focused on renewable generation capacity expansion. The ninth Electricity Supply and Demand Master Plan, CFI 2030 Plan, and the NRE Capacity cap all focus heavily on the supply plans of renewable energy. Plans with a focus on how much renewable energy should be supplied, which fail to present solutions to issues arising from the growth of renewables, have betrayed their limitations, including delays in integrating renewable energy into the power grid as well as frequent curtailment even after successful integration.

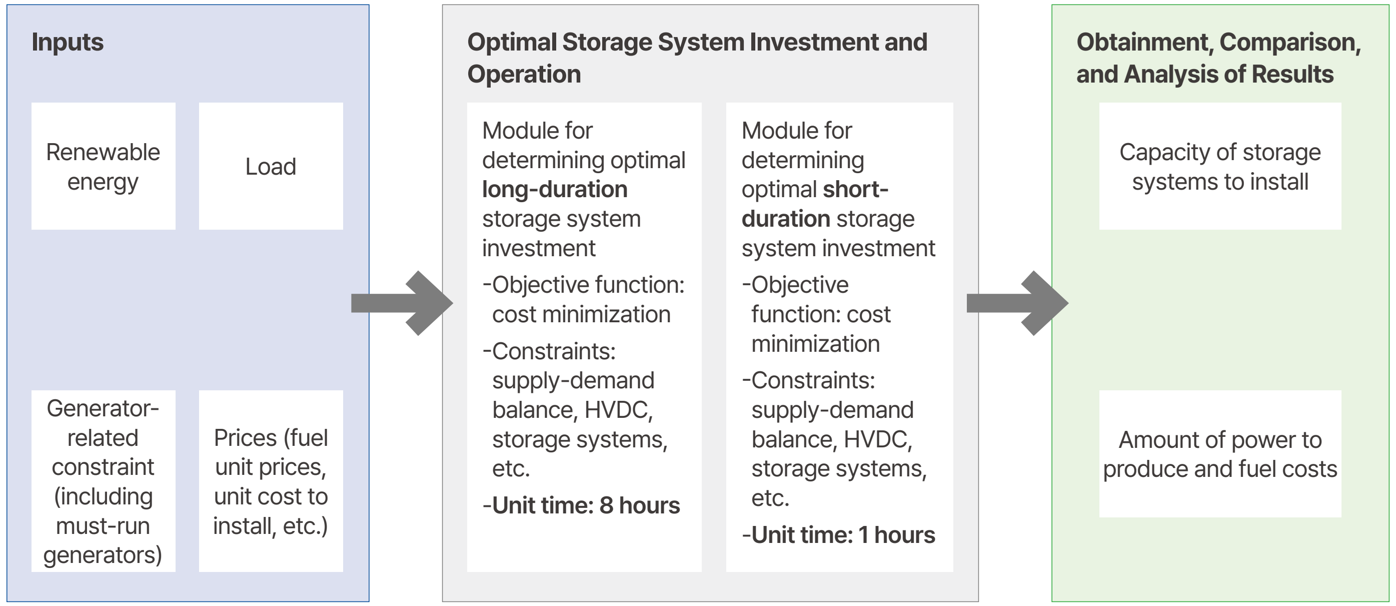
For trouble-free implementation of a plan to boost the penetration of renewables, the planners should simultaneously devise solutions to issues that the expansion of renewables may bring about. Jeju's second Comprehensive Wind Power Management Plan[47] discusses the **need to introduce storage systems and outbound HVDC transmission of power from Jeju to the mainland to reduce renewable curtailment** but does not suggest any tangible plans that reflect such factors. The required capacity of storage systems needs to be planned in light of the patterns of renewables and the changes in load over time. The yearly changes in the load and the renewable capacities necessitate annual planning for renewables.

Such short- and medium-duration systems as pumped water and battery energy storage systems (BESS) have been the main considerations as energy storage systems. However, the increase in the renewable supply plans is expected to cause oversupply to last for several days or more in the near future. To be able to deal with events of longer-lasting oversupply only with battery energy storage systems, they need to have significantly big capacities. Therefore, long-duration energy storage systems, which can store energy in great amounts at a lower cost, should also be taken into consideration.

This study employed an optimization method to construct an optimal storage system portfolio that reflects renewable supply target scenarios. The structure of the optimization model used in this study is shown in the figure below:

47 Jeju Special Self-Governing Province (2019) "The Second Comprehensive Wind Power Management Plan of Jeju Special Self-Governing Province," at https://www.jeju.go.kr/open/open/iopenboard.htm?act=view&seq=1171474

Figure 6. Methodology to Determine Optimal Storage System Investment



The inputs used for the optimization model are **renewable energy, load, generators, and prices. For the renewable energy inputs,**yearly renewable capacities, patterns, and curtailment were considered. For the yearly renewable capacities, the renewable plans presented either by the ninth Power Supply Master Plan or by the NRE capacity cap were used depending on the scenario, and for the renewable patterns, actual data[48] were used. The curtailment amount patterns were determined by, first, calculating the total yearly curtailment amounts by multiplying the total yearly renewable output by a certain ratio[49] and then, spreading the calculated values over the hours with the most excess supply.

For the load inputs, yearly peak loads,[50] load patterns,[51] and the like were considered, and the plans presented in the ninth Electricity Supply and Demand Master Plan were used.

48 For the solar power patterns, nationwide data that are searchable on public data portals were used. For the wind power patterns, data by the power generation complexes in Jeju and Jeollanam-do Province were used. The percentage, three percent, was used, which applied to Seongsan Wind Farm 2, one of Korea Southern Power Company (KOSPO)'s wind farms in Seoguipo-si, Jeju, in 2018.

49 For solar energy, a ratio from the solar generation facility owned by Sebang Co., Ltd (an inland transportation services company that has a strategic alliance with Korea Energy (KOEN)) in Gangyang, Jeollanam-do Province (2018) was used, and for wind power, three percent was used, which applied to Seongsan Wind Farm 2, one of Korea Southern Power Company (KOSPO)'s wind farms in Seoguipo-si, Jeju (2018).

50 Ministry of Trade, Industry and Energy (2020) "Ninth Power Supply Master Plan"

51 Ministry of Trade, Industry and Energy (2020) "Ninth Power Supply Master Plan"

The generator inputs , include heat coefficients and fuel costs and the **fuel unit prices among the price inputs** were adjusted in accordance with the individual fuel cost scenarios.[52] The minimum required power generation by the must-run generators and the incoming and outgoing HVDC transmission capacities were also included in the inputs in order to maintain reliability.

The optimum required capacities of the long and short duration storage systems were calculated through two stages, using two different unit times. In the first stage, we calculated the optimum required capacity of long-duration storage systems at the unit time of eight hours, and in the second stage, we calculated the optimum required capacity of short-duration storage systems at the unit time of one hour. The optimization calculation process yielded the required capacities of different types of storage systems, the charge and discharge amounts per hour, fuel costs for different energy sources, the amounts of power generation, and so forth.

- Objective Function

The study's objective function was to minimize the total costs, which included fuel costs, costs of installing storage systems, and so on. In determining the storage system installment costs, the residual values of the storage systems in the last year that reflect their remaining useful life were taken into account. For the discount rate used to obtain the present values of costs, the social discount rate (SDR) of 4.5 percent used by the Ministry of Economy and Finance for preliminary feasibility studies, which is 4.5 percent,[53] was applied.

- Constraints

The constraints of this study include power grid constraints, generator constraints, and storage system constraints. The power grid constraints include constraints regarding power supply-demand balance, inbound and outbound HVDC transmission, and the lower limits on generation by the must-run generators. The generator constraints reflect the upper limit on generation by each generator, while the storage system constraints include the state of charge (SoC), which considers the charging and discharging efficiency of the batteries, among others.

52 Article 50 of the General Guidelines on Preliminary Feasibility Studies (an order by the Ministry of Economy and Finance)

53 Article 50 of the General Guidelines on Preliminary Feasibility Studies (an order by the Ministry of Economy and Finance)

4-2. Scenario Design: Scenario Components[54]

In constructing the scenarios considered in this report, four main factors that have the biggest impact on resolving Jeju's curtailment issue (1. Renewable penetration plans, 2. Outgoing HVDC transmission capacity, 3. Fuel costs, and 4. Number of must-run generators to be replaced by synchronous condensers) were considered. Each key factor carries the following significance for the scenario construction:

1) Renewable Penetration Plans

Renewable penetration plans set renewable penetration targets and therefore have great impact on the determination of the required capacity of storage systems.

As explained earlier, Jeju originally planned its renewable targets in line with the ninth Electricity Supply and Demand Master Plan and the CFI 2030 Plan, but the recent prediction of nonstop rise of curtailment on the island motivated it to suggest the idea of an NRE capacity cap,[55] under which the island would keep reins on the pace of increasing renewables by downscaling its renewable energy generation capacity by 2025 or earlier while maintaining its penetration targets in 2030 and onward intact. The NRE capacity cap, as proposed, aims at lower cumulative new and renewable energy generation capacities by 2015 for both solar and wind than the original CFI 2030 Plan, by 138 MW and 1.3 GW, respectively,[56] but the former scheme's targets for 2026 and onward are the same as those of the latter.

We constructed **CFI 2030 Scenarios,** which are founded on the renewable energy targets by the ninth Electricity Supply and Demand Master Plan and the CFI 2030 Plan, and an **As-Is Scenario,** which employs an NRE capacity cap as a means of reducing curtailment. As a result, the total yearly renewable energy supply varies across the scenarios.

54 See Appendix ① for more detailed descriptions of the scenario components
55 GANG Seung-nam (2021) "Jeju to Control Wind & Solar Growth by Yearly Capacity Cap," at https://www.news1.kr/articles/?4524241 accessed on Sept. 7, 2022
56 GANG Seung-nam (2021) "Jeju to Control Wind & Solar Growth by Yearly Capacity Cap," at https://www.news1.kr/articles/?4524241 accessed on Sept. 7, 2022

Table 8. Scenarios for Jeju's Renewable Penetration Plans

Scenario Components	Scenario Notations	Scenario Descriptions
Scenarios for Jeju's Renewable Penetration Plans	T	Maintenance of the status quo (NRE capacity cap) (base)
	F	9th Electricity Supply and Demand Master Plan & CFI 2020 Plan

2) Outbound HVDC Transmission Capacity

The outbound HVDC transmission capacity is a critical factor in countering curtailment because it determines how much renewable oversupply could be sent away, meaning it has an influence on the total curtailment amount.

However, technical review is still underway to determine the outbound transmission capacity of the two HVDC tie-lines that are currently in commercial operation on Jeju, and a new HVDC tie-line is under construction. Therefore, for a more efficient analysis of the scenario analysis, we assumed a fixed outbound transmission capacity of 450 MW, which is the median of the scenarios for the outbound HVDC transmission capacity.[57]

To consider the differences in the outbound HVDC transmission capacity, we assumed two-bus systems, each comprising a Jeju bus, a mainland bus, and HVDC tie-lines connecting the two buses. At present, there are two HVDC tie-lines connecting the island to mainland Korea, which are HVDC Tie-Line 1 and HVDC Tie-Line 2. Another tie-line is under construction and is scheduled to be completed in 2024. We assumed the outbound transmission capacity of 70 MW, 140 MW, and 150 MW for HVDC Tie-Line 1,[58] HVDC Tie-Line 2,[59] and HVDC Tie-Line 3, respectively.

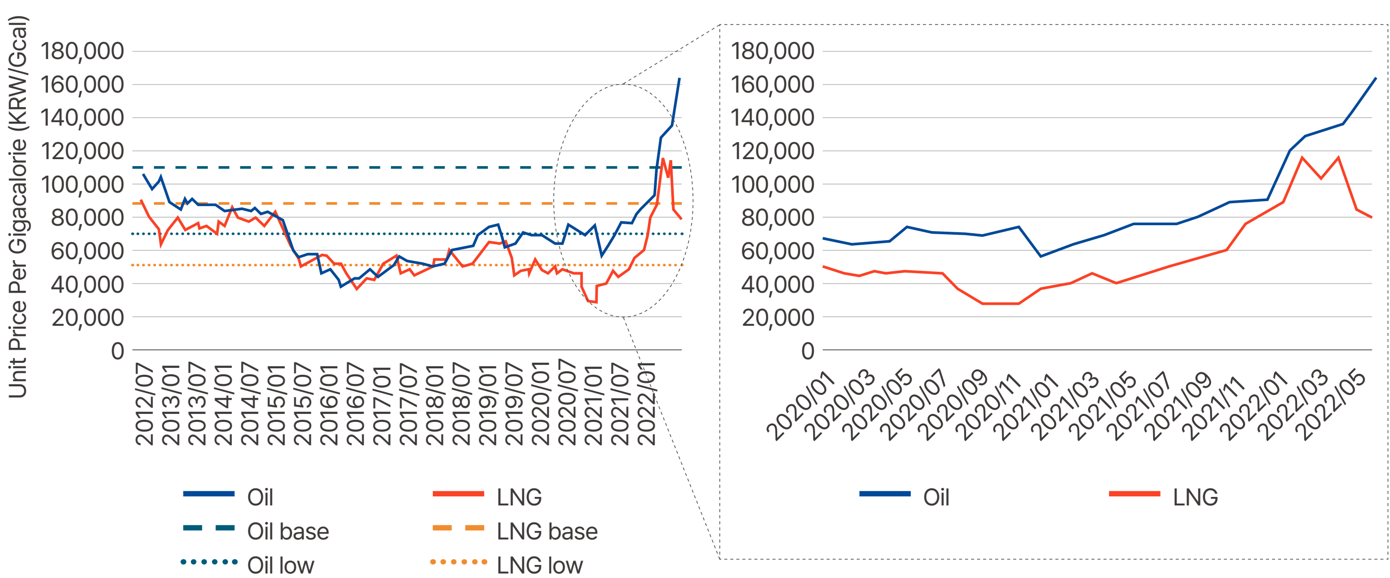
57 See Appendix ② for more details.
58 YU Hui-deok (Aug. 25, 2021) "Jeju's Curtailment Fails to Counter Suring Renewable Generation," The Electric Times at http://www.electimes.com/news/articleView.html?idxno=221824 accessed on Sept. 7, 2022; KWAK Eun-sup et al. (2021) "A Study on HVDC and BESS Application for High Penetration of Renewable Energy Sources," Journal of the KIECS
59 KWAK Eun-sup et al. (2021) ""A Study on HVDC and BESS Application for High Penetration of Renewable Energy Sources," Journal of the KIECS

3) Fuel Costs

Fuel costs is an important variable in analyzing the costs of each scenario aimed at countering curtailment. Particularly, it has the greatest impact on determining the total system cost (TSC) because, in Jeju's power grid, the heavy oil- or LNG-fired centrally dispatched generators are operated as must-run generators.

It should be noted that the fixed unit fuel cost of top five percent of the past ten years was applied to reflect more realistic levels of fuel costs and analyze the scenario results more efficiently.[60]
Figure 7 shows the prices per gigacalorie of different fuels over the past ten years (July 2012 -June 2022) and a more detailed look at the trend for the last one and a half years. Early this year (2022), Russia invaded Ukraine, catapulting the world into instability and driving the international community to impose sanctions on Russia, which is one of the largest LNG exporters. In response, Russia put restrictions on its LNG exports, sending the prices of LNG and other fuels soaring. Analyses have come out one after another projecting a depressing outlook that this upward energy price trend will not dissipate any time soon, including a prediction that this upward energy price trend may last into 2026.[61] More renewable energy generation leads to less use of fossil fuels, eventually to a huge reduction of fuel costs and carbon prices. If the fossil fuel prices per gigacalorie continue to stay at high levels, such a cutback on fuel-related costs will eventually lead to offsetting the total cost of investment in flexibility resources.

Figure 7. Fuel Prices over the Past Ten Years and the Recent Rises in Fuel Prices



60 See Appendix ③ for more details about the scenarios.
61 BloombergNEF (2022). Global LNG Market Outlook 2022-2026

4) Number of Must-Run Generators to Be Replaced by Synchronous Condensers

Given the nature of Jeju's power grid, the combined capacity of its must-run generators determines the power grid's capacity to accommodate renewable energy. Thus, the number of must-run generators that will have been replaced by synchronous condensers as a technical solution to increase the grid's renewable energy hosting capacity by 2025 is critical in determining how much storage system capacity will be needed and will greatly influence the pace of renewable expansion.

To ensure grid reliability, the Jeju power grid operator has designated the numbers of must-run generators to operate for different levels of load. Those must-run generators are assigned minimum amounts of power generation that are technically required to maintain grid inertia. That is, operating a certain number of must-run generators means that a certain level of must-run generated power must be maintained under any circumstances. This must-run generated amount is maintained even when renewable curtailment is necessary. Should there be a way to reduce the minimum required must-run generation without compromising grid reliability, it would be possible to increase the power grid's renewable hosting capacity while bringing curtailment below the expected levels or even to the very minimum.

Table 9. Must-Run Generators Replaced by Synchronous Condensers

Load	Current Operation Method	Replacement of 1 Must-Run Generator	Replacement of 2 Must-Run Generators	Replacement of 3 Must-Run Generators
500 MW or below	Namjeju Combined	Jeju Steam Power No. 2	Jeju Steam Power No. 2	Jeju Steam Power No. 2
	Jeju Combined Cycle No. 2	Namjeju Combined	Hallim Combined Cycle	Hallim Combined Cycle
	Jeju Combined Cycle No. 1	Jeju Combined Cycle No. 2	Namjeju Combined	Jeju Internal Combustion Nos. 1 and 2
	Namjeju Steam Power No. 2	Jeju Combined Cycle No. 1	Jeju Combined Cycle No. 2	Namjeju Combined
501 ~ 600(MW)	Jeju Steam Power No. 3	Namjeju Steam Power No. 2	Jeju Combined Cycle No. 1	Jeju Combined Cycle No. 2
601 ~ 900(MW)	Namjeju Steam Power No. 1	Jeju Steam Power No. 3	Namjeju Steam Power No. 2	Jeju Combined Cycle No. 1
901 MW or above	Jeju Internal Combustion No. 1	Namjeju Steam Power No. 1	Jeju Steam Power No. 3	Namjeju Steam Power No. 2
				: Modification of synchronous condensers

4-3. Results of Scenario Analysis

This study groups technical scenarios that address Jeju's renewable curtailment into two broad categories—an As-Is Scenario (which presumes to meet the targets by the NRE capacity cap) and CFI 2030 Scenarios (which presume to meet the CFI 2030 Plan)—and this report accordingly arranges the results of analysis of the scenarios, as well as their cost analysis .

Premises for Analysis

- We explained the four major components of the scenarios earlier, but we simplify the scenarios to present the results in a more effective manner. We focus on the renewable expansion plans and whether or not synchronous condensers replace must-run generators—two of the four components—in organizing the results. The outbound HVDC transmission capacity and fuel costs are set as constants.
- The carbon price forecasts that the Network for Greening the Financial System (NGFS) presents for Korea with the aim of limiting global warming to below 2°C are applied for the cost analysis of all the scenarios.
- The annual ratio of renewable curtailment to renewable output is assumed at three percent for both the As-Is Scenario and the CFI 2030 Scenarios, considering that the curtailment rate was at three-percent levels in 2019 in the six European countries of Germany, Denmark, the UK, Spain, Italy, and Ireland, where VRE is growing rapidly.
- The unit synchronous condenser installment cost is assumed at KRW 45,247 per kVAR.[62]

The **As-Is Scenario**[63] is presumed to meet the targets of the **NRE capacity cap** by eliminating oversupply mainly through curtailment without additionally introducing new technologies like energy storage systems and synchronous condensers.

Under the **CFI 2030 Scenarios,**[64] the **CFI 2030 Plan** and the **ninth** Electricity Supply and Demand Master Plan are accomplished by introducing energy storage systems and/or synchronous condensers to counter oversupply.

62 The unit installation cost is assumed at 40 USD/kVAR, and the exchange rate is assumed to be 1,131 KRW/USD, which is the median of the annual averages over the past ten years (2012-2021).
63 See Appendix ⑤
64 See Appendix ⑥

The analysis results of the three technical scenarios, as well as their cost analysis results, are as follows:

Table 10. Components of Each Scenario and Summaries of Scenario Analysis Results (2034)

Scenario	Components of Scenario					Scenario Analysis Results (2034)				
	Solar and wind generation capacity (MW)		Cumulative storage system capacity (MW; 2034)		Synchronous condensers	Power plant utilization rate			Curtailment rate	Total system cost (TSC) *2022-2034 TNPV (cost-benefit vs. As-Is) (KRW)
	2022	2034	Battery energy storage system	Hydrogen storage system		Traditional power supply equipment (LNG, heavy oil, HVDC transmission) (Utilization rate compared to 2022)	Solar	Wind		
As-Is	1,031	3,982	0	0	No	25.6% (▼13.4%)	10.1%	19.4%	19.2%	3.5Tn
CFI 2030	1,634	3,982	678	1,525	No	23.0% (▼ 16.0%)	13.2%	24.2%	3.0%	6.4Tn (▲ 2.9Tn)
			614	536	Yes	20.1% (▼ 18.9%)	13.2%	24.2%		3.7Tn (▲ 0.2Tn)

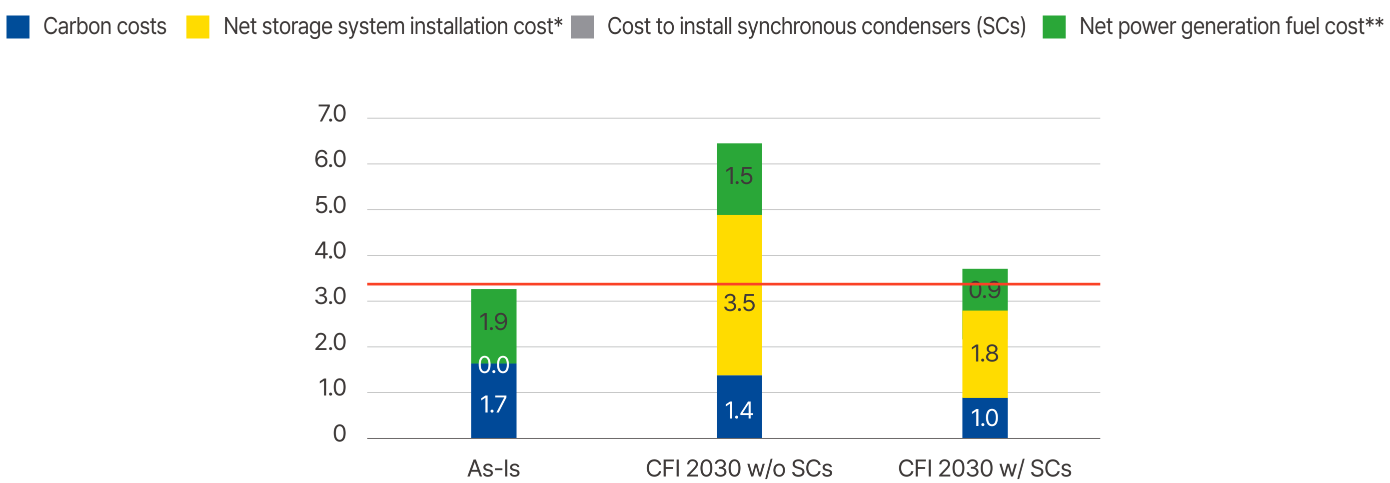
First, Jeju can implement the CFI 2030 Plan and the ninth Power Supply Master Plan while maintaining its renewable curtailment rate at three percent. It is necessary to replace three of the fossil fuel-powered must-run generators that are currently in operation on Jeju by synchronous condensers and to introduce other flexibility resources including storage systems with capacity of 1,151 MW by 2034. The analysis has confirmed that the introduction of such means will help secure resources required to maintain grid reliability, making it possible to expand renewables per the CFI 2030 Scenario with synchronous condensers (i.e., one of the two CFI 2030 Scenarios that introduces synchronous condensers) while holding the curtailment rate at three percent or below.

Second, the CFI 2030 Plan is achievable if a cumulative total system cost of up to 5.7 percent of the As-Is Scenario (KRW 0.2 trillion) is invested by 2034 even if the renewable curtailment rate is maintained at three percent. Under the As-Is Scenario with the highest renewable curtailment rate of 19.2 percent, the total system operation cost is expected to reach KRW 3.5 trillion by 2034. If an additional investment equivalent to 5.7 percent of the cumulative total system cost is made to install synchronous condensers and storage systems, it would be still possible to achieve the CFI Plan while maintaining the curtailment rate at 3.0 percent, according to the analysis.

* 2022-2034 total net present value (TNPV)
**Such social costs as fuel costs (heavy oil and LNG) and carbon costs are included. The Korean references presented by the Network for Greening the Financial System (NGFS), a global network of central banks and supervisory authorities advocating more sustainable financial systems, are applied.

The total system cost under the CFI 2030 Scenario featuring synchronous condensers is expected to reach KRW 3.7 trillion, including a net installation cost of KRW 1.9 trillion for replacing three must-run generators with synchronous condensers and introducing battery energy storage systems (BESS) with a combined capacity of 614 MW and hydrogen storage systems with a capacity of 536 MW. On the other hand, under the As-Is Scenario that attempts to eliminate VRE oversupply by means of curtailment without introducing such flexibility resources as storage systems and synchronous condensers, the total system cost amounts to KRW 3.5 trillion, which reflects high fuel costs and carbon costs attributable to continued heavy dependence on fossil-fuel-based power generators. It has been confirmed that, under the CFI 2030 Scenario, the cost incurred by the installation of additional storage systems may be offset by reducing the fuel costs and carbon costs.

Figure 8. Total System Cost for Different Components by Scenario (Unit: KRW 1 Tn)

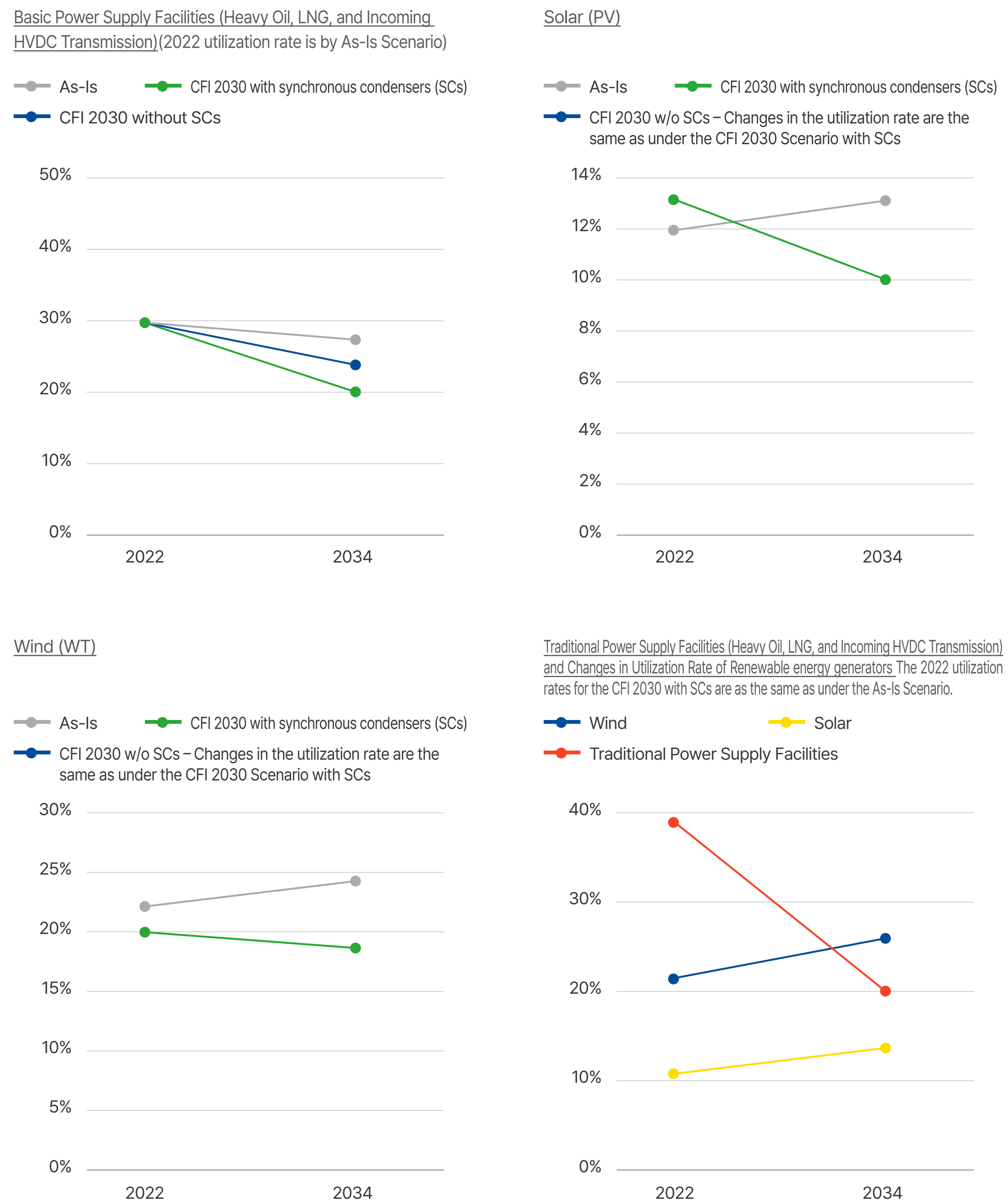


* Net installation costs for storage systems: The costs to install the storage systems less their residual value at the end of 2034

** Net fuel costs for power generation: Jeju's fuel costs for generating power less or plus the fuel costs that are added to or deducted from the mainland's fuel costs in consideration of incoming or outgoing HVDC transmission of power. For the mainland's fuel costs, 158 KRW/kWh (which represents the top five percent LNG costs of the last ten years) is used for the base scenario, and 96 KRW/kWh (which is the median of the LNG costs of the last ten years) is applied for the low scenario.

Third, if such flexibility resources as storage systems and synchronous condensers are introduced under the CFI 2030 Scenario, the utilization rate of the traditional power supply facilities (including the heavy oil-or LNG-fired fossil-fuel-based power plants owned by the generation subsidiaries of KEPCO) would decrease by as much as 19 percentage points from the 2022 level by 2034. Introduction of such flexibility resources as storage systems and synchronous condensers will lead to an increase in the utilization rate of the renewable energy generation facilities, but pull down the utilization rate of the traditional power supply facilities (including the incoming HVDC transmission systems and the fossil-fuel-based power plants owned by KEPCO's generation subsidiaries) to 20+ percent in 2034, a decline of up to 19 percentage points from the 2022 level.

Figure 9. Changes in the Utilization Rates of Traditional Power Supply Facilities and VRE Power Plants



As illustrated above, adoption of the CFI 2030 Scenario would lead to an increase in the utilization rates of renewable energy and flexible resources including storage systems, but the internal rate of return (IRR) of energy storage systems would be significantly low if the current settlement structure were to be maintained. For each of the two CFI 2030 Scenarios, the average internal rate of return was calculated for battery energy storage systems (BESS) and hydrogen storage systems (HSS) in consideration of their installation costs, residual values,[65] capacity payments,[66] and revenue from energy arbitrage.[67] The results are shown in the table below:

Table 11. IRRs of Storage Systems Under the CFI 2030 Scenarios

Scenario	CFI 2030 w/o SCs	CFI 2030 w/ SCs
Avg. BESS IRR	-5.2%	-4.7%
Avg. HSS IRR	-7.5%	-9.0%

Under both CFI 2030 Scenarios, negative IRR was predicted, meaning that investing in storage systems would not generate any profit under the current settlement structure. As illustrated in the above scenario analysis, installation of ESSs to counter curtailment is essential to utilize renewable energy facilities more effectively in Jeju. Therefore, it is pivotal to improve the settlement structure.

65 The useful lives of battery energy storage systems (BESS) and hydrogen storage systems (HSS) were all assumed at 20 years.
66 Jeju's unit capacity price (22.05 KRW/kW) and rule on the effective capacity rates of energy storage systems were applied.
67 System marginal prices (SMP) for different levels of load were considered. That is, revenue from energy arbitrage was calculated under the assumptions that the SMP at the time of charging is 184.7 KRW/kWh and that the SMP at the time of discharging ranges from 201.4 KRW/kWh to 226.4 KRW/kWh.

Implementation of either of the two CFI 2030 Scenarios would lead to a decline in the utilization rate of the traditional power supply facilities including fossil-fuel-based power plants which would in turn result in a decline in revenue in the consolidated financial statements of KEPCO and its generation subsidiaries, exerting a direct financial impact on them. In addition, KEPCO and its generation subsidiaries can wield influence on relevant issues because they retain substantial voting rights on the Electricity Market Operation Committee (an arm of the KPX), the KPX board of directors, and the general assembly of KPX members, which make decisions on compensation and grid connection issues. Therefore, measures that not only increase the independence of KPX's decision-making processes but also sever the financial ties between KEPCO's power generation and power grid businesses should be prioritized. Then, a conducive environment would be created for KPX to take proactive and impartial measures to enhance the utilization of flexibility resources and renewable energy.

Meanwhile, under either of the two CFI 2030 Scenarios, the fall in the utilization rate of renewables is insignificant and can be maintained at a certain level. This is because the annual renewable curtailment rate is maintained at a three percent level by utilizing ESSs and synchronous condensers. These analysis results demonstrate that extensive introduction of flexibility resources such as storage systems and synchronous condensers will help boost renewables without compromising the interests of renewable businesses.

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5. Conclusion and Suggestions

The analyses thus far lead to the conclusion that introduction of such flexibility resources as energy storage systems (ESS) and synchronous condensers can significantly contribute to Jeju's efforts to counter renewable generation curtailment by lowering the utilization rate of its traditional power supply facilities, including fossil-fuel-based power plants, while maintaining the utilization rate of renewable energy.

Moreover, introduction of an optimal level of flexibility resources aimed at resolving curtailment would see a rise in the total system cost (TSC) for a short time, because of their installment costs, but over the mid- and long-term, the increase in the total system cost could be relatively insignificant when also factoring in the social costs (e.g., fuel and carbon cost) that would be incurred otherwise. In other words, the total system cost will be only KRW 0.2 trillion more than a scenario in which VRE oversupply is eliminated exclusively through curtailment without resorting to any technical solutions.

Additionally, implementation of a CFI 2030 scenario will eventually lead to a decline in the utilization rate of the traditional means of power supply including fossil-fuel-based power plants, which would in turn erode revenue in the consolidated financial statements of KEPCO and its generation subsidiaries (which own those traditional power supply facilities), exerting a direct financial impact on them. At the same time, KEPCO and its generation subsidiaries may exert a significant level of influence on grid access and compensation, as they retain substantial voting rights on the KPX Electricity Market Operation Committee, the KPX board of directors, and the general assembly of KPX members. Therefore, measures that not only increase the independence of KPX's decision-making processes but also sever the financial ties between KEPCO's power generation and power grid businesses should be prioritized. Only then would a conducive environment be created for KPX to take proactive and impartial measures to enhance the utilization of flexible resources and renewable energy.

It is also important to transform the market and regulatory landscapes in a way that will facilitate the introduction of such flexibility resources as energy storage systems, synchronous condensers, and demand response, but the bleak profitability outlook has prevented flexibility resources from entering the market quickly enough. In particular, revenue is generated by means of energy arbitrage settlements[68] and capacity payments in the energy storage system business, but no meaningful revenue can be made from energy arbitrage under the current power market structure because the energy rate remains almost the same regardless of season or between peak and non-peak hours of the day. The capacity payments (CP) that are applied to battery energy storage systems (BESS) are very low because the payments are made only for the battery capacities. Among all of the internal rates of return (IRRs) of battery energy storage systems obtained under the CFI 2030 scenarios that this report considers are negative, with the smallest being −9 percent.

Such results suggest that if the current settlement structure was maintained, ESS would garner practically no return on investment. This implies that investors alone need to bear all economic risks arising from their investments in flexibility resources, which understandably demotivates them. This stands in stark contrast with the fossil-fuel-based generators owned by KEPCO's generation subsidiaries, which receive about 22.05 KRW/kWh[69] for 24 hours and are guaranteed a fair level of profits, along with reimbursement of fuel costs and capital investment costs under a cost-plus mark-up guarantee scheme regardless of how high or low their utilization rates are, with the exception of emergency situations that threaten the plants themselves.[70]

The current system that excessively and unnecessarily guarantees profits for fossil-fuel-based power generators hinders fair competition with renewables and flexibility resources. Fossil-fuel-based power generators, which rely on the guaranteed fair level of profits, will not be ousted from the market even when their economic viability declines, and will continue to be given priority in determining Jeju's power generation mix, thereby limiting renewables' market participation. Not only that, the delayed introduction of flexibility resources, which are not guaranteed a healthy level of profitability, makes it harder to reliably integrate renewable energy into the grid. This would, in turn, trigger more frequent curtailments and ultimately slow down the expansion of renewables.

68 Energy arbitrage uses the gap in the electricity rate between the time of charging and discharging in cases in which energy storage systems are charged when the rate is low and discharged for use when the rate is high. [Ministry of Environment, Korea Environmental Industry & Technology Institute (KEITI) (Feb. 13, 2017) "Energy Security-Oriented ESS Industry and Its Trend."]
69 The reference capacity price on the mainland is 11.85 KRW/kWh (KPX, Cost Assessment Rules).
70 In 2019, Jeju introduced capacity prices in order to reinforce system stability in the face of the variability of renewable energy. In doing so, the island classified its bio-heavy oil-fired generators as scheduled generators. The capacity price payments that Jeju made for the heavy oil- or LNG-fired generators that KEPCO's generation subsidiaries own and operate on the island amounted to KRW 126.3 billion in 2019.

In this light, the report suggests the following improvements to introduce an economically viable scenario that 1) does not slow down the expansion of renewables and 2) limits the curtailments under a certain threshold on Jeju Island:

First, the government should be more proactive in devising measures to improve the power market and the grid systems.

Second, the government should formulate an fair compensation scheme in order to promote a more expansive use of such flexibility resources as storage systems and synchronous condensers, thereby minimizing renewable generation curtailment

Third, the government should prevent fossil fuel generators from receiving excessive compensation benefits denied to their renewable counterparts by improving the cost-plus mark-up guarantee scheme and limiting the volume and eligibility criteria of the Capacity Payment (CP) for fossil-fuel-based generators.

Finally, the current power grids centered around fossil-fuel-based power generators are, inevitably and by nature, constantly vulnerable to volatility in prices and supply in the global market. In light of the forecasts that fuel prices will remain as high as they are now at least for the next four or five years[71] plus the upward global carbon price trend, fossil-fuel-based-oriented power grids will incur increasingly higher costs in the longer term. To minimize the financial risks that its power grids will face relatively soon, Korea needs to address the root causes of renewable generation curtailment and continue to expand the use of renewables.

Introduction of other flexibility resources (e.g., demand response and sector coupling) and a compensation scheme limiting renewable generation curtailment will be critical factors in creating a level playing field where renewables can grow and thrive through fair competition.

71 BloombergNEF (2022). Global LNG Market Outlook 2022-2026

Jeju's 2030 Carbon-Free Vision Begins With Renewable Curtailment Freedom:

Cost Analysis of Solutions to Renewable Curtailment on Jeju Island, South Korea