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Optimal capacity expansion pathway of renewable energy and energy storage under 2050 net-zero in South Korea

2050 탄소중립 실현을 위한 최적 재생에너지와 에너지저장장치 설비 용량 계획

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Abstract

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Renewable energy is being presented as a sustainable solution to the problems raised by the climate crisis. Accordingly, the Korean government is also considering renewable energy and nuclear power as means of achieving carbon neutrality in the power sector. However, due to the output fluctuation and intermittency of renewable energy, Energy Storage System (ESS) is required. The ESS device stores surplus power as other types of energy and discharges it back into the grid during high load times to relieve power supply instability caused by renewable energy. However, unlike renewable energy, where detailed capacity expansion plans are continuously established, specific plans for energy storage devices are being delayed. Accordingly, the capacity expansion planning model is employed to emphasize the need for the simultaneous planning of renewable energy and energy storage devices and compare the cost and the amount of device capacity required to

achieve carbon neutrality and the total curtailment with the result of individual planning. In addition, ESS as a facility that is still not commercialized as renewable energy technology, the uncertainty of the cost prediction exists. Therefore, the impact of cost reduction speed - which represents technology development – on the result is also investigated.

The result shows that co-optimization reduced the amount of renewable energy facility required to achieve carbon neutrality by 2050, and also reduced the total cost for capacity expansion and operation. In addition, it was shown that the curtailment of renewable energy was greatly reduced, in other words, the operational efficiency of renewable energy in carbon neutrality was also improved. Meanwhile, the acceleration in the speed of ESS technology development creates a synergy that primarily induces an increase in the size of ESS, furthermore, decreased the demand for renewable energy capacity. Consequently, the total cost diminished. Besides, the curtailment is also mitigated with the acceleration of cost reduction speed.

This study emphasizes the need for co-optimization planning of renewable energy and ESS facilities to Korean policymakers, and at the same time helps them understand the changes that might take place when the technology development rate of energy storage varies. In addition, unlike previous studies, the time resolution of facility operation was set to one hour to describe the volatility of renewable energy output and the charging and discharging decisions of ESS in more detail. Thus, the result of capacity expansion planning could reflect a more realistic quantity demand for the facilities.

Keywords: Renewable energy, ESS, power system optimization, capacity expansion planning, zero emission

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Chapter 1. Introduction

1.1 Background

1.1.1 Renewable energy in the Korean power sector

Concerns regarding climate change due to greenhouse gas emission caused by human activity has been spread worldwide. And the greenhouse gas produced by various human activities is proven to be the major cause of climate change ("The IPCC Sixth Assessment Report on Climate Change Impacts," 2022). The carbon dioxide emission from fossil fuels has been rising since 1900. To deal with the climate issues that appeared, governments should urgently make appropriate policies to guide each sector of the country to find ways to mitigate carbon emissions. For some sectors such as the power sector, transformation of the entire industry's structure is inevitable (Oh et al., 2021). For instance, the energy sector, has the biggest emission scale of carbon dioxide. The majority of the emission from the energy sector is caused by the fossil fuel combustion to generate electricity and heat.

According to the 10^{th} Basic Plan for Long-term Electricity Supply and Demand (BPE) (Government of Korea, 2023), the power sector of Korea is planned to achieve zero emissions within 2050 without considering CCUS (Carbon Capture Utilization and Storage). And the power sector in South Korea has set a goal to limit its carbon emission by 149.9 tons of carbon dioxide by 2030 according to the Enhanced Update of the First Nationally Determined Contribution (Enhanced NDC) (Government of Korea, 2021). The key technologies proposed in the plan are renewable energy and nuclear power plant. Around 55% of the generation share is to be reached in 2030 by nuclear and renewable energy sources, respectively. As Oh et al. (2021) argued, the goal is rather challenging. Furthermore, renewable energy implementation is a way of achieving carbon neutrality, but the aforesaid shortcomings make it tough to take charge of a large amount of electricity supply by itself (Zhou et al., 2021). To handle this issue, Energy Storage System (ESS) could be the solution.

An energy storage system is regarded as an effective remedy to relieve the unstable supply of renewable energy. It improves system stability by storing idle electric energy by converting it into other forms of energy and releasing it in peak load times without letting dispatchable units to fill up the gap (Ibrahim., 2008). Moreover, unlike dispatchable units, ESS is free from the constraints of ramp time & cost, which enables capturing the instantaneous change in the power output of renewable energy. Furthermore, ESS can reduce the required capacity of dispatchable generation units (Javadi., 2019). In this respect, ESS is highly recommended in the high renewable penetration power system. Therefore, when planning a capacity expansion plan in a country scale, the interaction between ESS and renewable energy should be within consideration.

1.1.2 The current policy of Korea

The power sector of Korea is one of the main sectors requires drastic transformation to attain carbon mitigation. Plenty of plans and roadmaps are made for the power sector, especially for renewable energy and ESS. The Fifth Basic Plan for New and Renewable Energy Development, Utilization and Supply (BPR) (Ministry of Trade, Industry and Energy, 2020) has mandated the power sector to rise the generation share of renewable energy to 25.8% till 2034, in conformity with 9th BPE and 3rd Basic Plan for Energy Supply and Demand. The increment from 2019 is 20.2%p. In accordance with the growth of renewable energy share, it also designated the Virtual Power Plant (VPP), ESS, and gas turbine technology as solutions for unstable generation.

However, the Enhanced NDC (Government of Korea, 2021) did not take the problems of high renewable energy penetration system might have seriously. They namely enhanced the 2030 renewable share goal to 30.2% to relieve carbon emissions without considering any clue of flexibility and reliability of the grid operation. In other words, the plan is made without method.

The 2050 Carbon neutrality scenario (Government of Korea, 2021) was released to move a step forward to the 2050 carbon neutrality realization. It embodied the details of final goals, claims that the power sector is to eliminate fossil-powered generators in 2050 in plan A, or retain 5% of the electricity supply share of the LNG in plan B. The plan A requires 70.8% of the renewable energy supply share and 60.9% in plan B. Also, it was proposed that the technology of storing, transforming and reuse of idle electricity requires attention.

The 10th BPE is the most specified long-term plan for devices of the power sector. The plans for fire-powered units and renewable energy expansion are set yearly in detail. Moreover, the ESS device is considered to deal with the fluctuation and intermittency that renewables make. However, the plans for ESS are not projected as detailed as generation units, only the uncertain long-term goal is made. According to the 1st Basic Plan of National Eco-friendly Development (Government of Korea, 2023), the Government pointed out that renewable energy and nuclear power plant are the 2 key technologies to achieve zero carbon emissions by 2050. In addition, coal power plants with a life span of more than 30 years are planned to be banished. That is to say, electricity generation and supply is facing a huge shift from fire-powered generation to renewable energy generation.

1.2 Research gap identification

In one hand, the Korean Government is predicting electricity supply, demand, and their balance yearly. On the other hand, according to the balance, plans for generation unit expansion including renewable energy sources are being made. However, the energy storage's expansion plan is not detailed enough in comparison to renewable energy. The plan is ambiguous in that type of energy storage is not designated and the plan is not made in yearly scope but in 4 or 6 years. As previously mentioned, energy storages are essential in operating grid with high-renewable energy penetration. Spare electric energy is stored in other energy forms, and discharged when needed. This interaction between renewable generators and energy storage is where the demand for storage comes from. The more renewable penetration, the more storage is needed to maintain grid stability (Yosef et al., 2021). In this respect, planning renewable energy capacity and energy storage together is necessary.

The renewable unit-energy storage interaction needs to be simulated in seconds because the power of renewable units varies in every second. However, the majority of the previous research (Gantz et al., (2012), Min et al., (2018), Rajesh et al., (2016), da Luz & Moura (2019)) conducted capacity expansion planning have set more than several hours, even a year as the smallest time piece in the model. Therefore, this study is setting 1 hour as the time piece to focus on the realistic portrayal of renewable energy and energy storage’s interaction. Moreover, we expect for more sophisticated time scale to result in more accurate demand of the facilities' capacity in the optimization model.

Meanwhile, as projected in Schmidt et al. (2019)’s paper, the unit cost of energy storage is going to vary each year. Moreover, the cost reduction rate is different for each type of storage technology. Thus, the cost variation of storage technology should be considered instead of applying fixed unit cost in a long-term planning model. The difference in technology development speed will result in different technology selections in each year by 2050 carbon neutrality.

To sum up, this study attempts to make an appeal to the Korean Government to plan renewable energy and energy storage simultaneously considering the cost change of storage technologies. In order to reflect the practical demand of device size, a 1-hour time unit is selected in describing renewable energy fluctuation and ESS operation. In addition, we also paid attention to the uncertainty of ESS cost prediction. Therefore, the additional scenarios are set under different technology development to analyze the distinctions among results.

1.3 Thesis overview

This paper consists of the following sections. A comprehensive literature review regarding the research area and model establishment will be presented in Section 2. Section 3 describes specific information about the employed model with input data, and equations, including objective function and constraints and scenarios. Section 4 displays the solution from the model, the interpretation of the result, and visualization. Section 4 will also contain comparisons of the scenarios. Lastly, the conclusion and policy implications according to the result in Section 4 will be provided in Section 5, direction of the future work, and limitations as well.

Chapter 2.   Literature review

2.1 Power system optimization

Power system optimization is often used to systematically analyze power system-related objects. For instance, Ahmadi et al. (2019) proposed a framework of unit commitment model considering the uncertainty caused by V2G implementation. A microgrid is a grid entity that can be controlled independently of the main grid, with has loads and distributed energy sources. Khorramdel et al. (2016) analyzed electricity supply reliability in a microgrid when energy storage is installed. Xu. et al. (2020) provided adaptive dynamic programming under the interconnection of gas-power network on the unit commitment's basis. In preparation for the advent of the electric vehicle(EV) era, interactions between EV systems and power systems are studied. Ali et al. (2020) optimized the size and location of solar panels and EV charging systems. Langenmayr et al. (2020) tried to figure out the optimal local control method considering EVs and photovoltaics.

2.2 Capacity expansion planning model

Capacity expansion planning(CEP), is one of the power system optimization models, which is used to determine optimal size, location, type of technology of generation plants, and relevant facilities. (Koltsaklis &Dagoumas, 2018) Recently, various efforts are being made to identify the optimal solution for the renewable energy source using capacity expansion planning model.

Samuel et al. (2022) combined Electricity demand forecasting and the CEP model to make it more realistic to simulate the problem of Tamil Nadu, an Indian state. In the model, the author included uncertainties from load, cost, forced outage rate, and capacity credit of the power plants. Park et al.

(2019) studied renewable energy supply in hour-scale to find the optimal renewable energy mix in South Korea. Min et al. (2018) conducted long-term capacity expansion planning for large-size renewable energy technologies using stochastic programming. The following contents contain capacity expansion planning considering renewable energy or energy storage.

2.2.1 Renewable energy and energy storage

Renewable energy and energy storage are considered as one of the practical technologies to be analyzed within the power system optimization model. Wen et al. (2020) dealt with the problem that the intense fluctuation of wind power generation will cause accelerated battery degradation, and introduced a new system optimization model covering hydrogen conversion systems. Jeon & Lee (2019) utilized the stochastic optimal power flow model to investigate and identify the types of uncertainty stemming from renewable energy sources. Rajesh et al. (2016) implemented a differential evolution algorithm in solving expansion planning models with solar power plants. Da Luz & Moura (2019) presented a novel objective function that is to electricity mix and the water flow of hydropower reservoirs. Li et al. (2020) proposed an objective function to maximize the utilization of renewable energy during the short-term planning horizon. The multi-agent-based approach of the CEP model was proposed in Paliwal et al. (2022)'s paper, minimizing total life cycle cost considering renewable energy. Moreover, the objective function refunds salvage value at the end of the planning horizon on a utility lifetime basis. Asensio et al. (2017) considered demand response in the bi-level optimization in which the first stage is the capacity expansion cost minimization. In Abbas et al. (2018), the objective function, the total cost is defined with investment cost, fuel cost, operation and maintenance cost. Heuberger et al. (2017) provided the idea of cost-diminishing technology considering energy storage. They distinguished the investment cost into a part under learning effect and part without learning effect. Additionally, Heuberger's model is made single-noded like the model used in this study. Lv et al. (2020)'s model minimizes the total cost with investment cost, operation & fuel cost, demand side investment cost and subsidy constrained with noxious gas emission and grid flexibility constraints.

As for renewable energy source is technology full of uncertainty in their generation patterns, the intermittent behaviors are addressed by the stochastic capacity expansion planning model in some previous research. Part et al. (2016) conducted multi-year stochastic generation expansion planning to analyze the impact of environmental energy policy on generation capacity and carbon emission. Min et al. (2018)'s study also involves stochastic programming with Loss of Load Probability (LOLP).

As Sani et al. (2020) and Dagoumas & Koltsaklis (2019) summarized, the capacity of renewable energy and energy storage should be planned systematically on a country-scale. This study referred to aforesaid previous literature to compose an apposite model to plan country-scale sizing. The literature provided with constitution of the constraints and objective function, the structure of the model, and the equations. A detailed model description constructed in this study is in the next chapter.

Chapter 3. Methodology

This Chapter introduces the model and its detailed contents.

3.1 Input data

Input data and its source is arranged in Table 1.

Table 1. List of input data

Input data description	Source	Unit
Renewable energy capacity before 2023	Epsis	MW
Determined capacity plan of renewable facility till 2036	10th Basic Plan for Long-term Electricity Supply and Demand	MW
Historical hourly data of electricity demand in 2022	KPX	MW
Unit cost of wind and solar facility	Park et al. (2019)	Thousand won/MW
Unit maintenance cost of wind and solar facility	Min et al. (2018)	Thousand won/MW-year
Lifespan of renewable generation facility	Park et al. (2019)	Years
Cost projection of renewable generation facility	Huh et al. (2014)	%
Hourly capacity factor(availability factor) of renewable energy	Calibrated by KPX data	%
Determined capacity plan of the dispatchable unit till 2036	10th Basic Plan for Long-term Electricity Supply and Demand	MW
Fuel cost	Epsis	won/Gcal
Emission coefficient of dispatchable units	KPX	CO2kTon/MWh
Reserve margin	10th Basic Plan for Long-term Electricity Supply and Demand	%
Annal upper bound of carbon emission	1st Basic National Eco-friendly Development Plan	CO2kTon
Technical parameters of energy storage	Schmidt et al. (2019)	
Discharge time	Kebede et al. (2022)	Hours
Energy storage capacity before 2023	Status of Electrical Facility (2023)	MW and MWh
Technical parameters of PHES	KEEI (2020)	
Determined capacity plan of PHES till 2036	10th Basic Plan for Long-term Electricity Supply and Demand (2023)	MW and MWh

More detailed parameters of ESS technology are listed in Appendix 1.

3.1.1 Calibrated data

The hourly demand data shown above is projected to 2036 according to the target demand announced in the 10th Basic Plan for Long-term Electricity Supply and Demand keeping the demand pattern unchanged. The demand in the following years (2037~2050) is projected linearly using the average demand growth rate of the last 3 years (2034~2036).

Renewable energy generators and energy storage systems already have capacity before 2023. To represent the Korean facility status, the initial capacity is available in the model and perishes in accordance with the facility's utility life. For instance, the lithium battery energy storage with 13 years of life will remain at 53.8% of its capacity after 6 years.

The capacity of nuclear power plants remains until 2050 for the government has announced the use of nuclear power plants (Government of Korea, 2023).

The carbon emission target of the Korean Government has only been unveiled for up to 2036. Target after 2036 is assumed to linearly decrease the emission until reaching zero emission in 2050.

The fuel consumption of a power plant i is as Eq.(1) when H_i represents heat consumption(Gcal/h) P_i for power output(MW). QHC, LHC, and NLHC stands for Quadratic Heat rate Coefficient, Linear Heat rate Coefficient, and No Load Heat rate Coefficient with unit of Gcal/MW^{2}h, Gcal/MWh and. Gcal

$$H_i = QHC_i P_i^2 + LHC_i P_i + NLHC_i \qquad \text{Eq.(1)}$$

Its quadratic form needs to be approximated to linear form to apply in a linear programming model. Eq.(2) computes the cost of heat production(won) at its maximum output by multiplying Eq.(1) by Fuel cost(won/Gcal).

$$Cost\ \ of\ \ Heat\ \ production = Fuel\ \ cost * (QHC_i P_i^2 + LHC_i P_i + NLHC_i) \qquad \text{Eq.(2)}$$

Then, dividing both sides of Eq.(2) with power plant capacity(MW) will yield the approximated 'Fuel cost'(won/MWh).

3.1.2 Diminishing investment cost of renewable energy generators and energy storage

As mentioned above, the unit investment cost of the renewable unit and energy storage is decreasing in accordance with the lapse of time. Referring to Huh et al. (2014)'s work, the predicted unit cost and LCOE (Levelized Cost of Energy) of renewable energy are shown in Table 2.

Table 2. Cost of renewable energy generator

Year	Unit cost of wind(Million won/MW)	Unit cost of solar(Million won/MW)	LCOE of wind(Million won/MWh)	LCOE of solar(Million won/MWh)
2023	2548	2184	55.8	70.5
2030	2451.9	1523.8	53.7	49.2
2036	2373	1121.7	52	36
2040	2321.9	914.6	50.9	29.6
2043	2284.2	784.7	50.1	25.4
2047	2235	639.8	49	20.7
2050	2198.7	548.9	48.2	17.8

The cost-decreasing rate of solar power is significantly higher than wind. The LCOE of wind power is lower than solar power in 2023 but reversed in 2030. Moreover, the LCOE of wind power reaches 2.7 times that of solar power in 2050.

The estimated future cost of energy storage is presented in Table 3. Symbol Li, PHES, and HSS represent lithium-ion battery ESS, Pumped Hydro Energy Storage(PHES), and Hydrogen Storage System(HSS), respectively. The unit of power cost and energy cost are million won/MW and million won/MWh.

Table 3. Cost of Energy storage system

Year	Unit power	Unit power	Unit power	Unit energy	Unit energy	Unit energy

	cost of Li	cost of PHES	cost of HSS	cost of Li	cost of PHES	cost of HSS
2023	263	1298	4309	311	92	25
2030	89	1298	2862	105	92	16
2036	41	1311	2146	48	92	12
2040	27	1311	1859	31	93	10
2043	21	1311	1730	25	93	10
2047	14	1324	1558	17	93	9
2050	9	1324	1430	10	94	8

The slope of cost decline differs from each technology. Thus, the 'cheapest' technology is expected to change from time to time.

3.2 Model description

3.2.1 Model structure

The capacity expansion model for this study was constructed in a single-node form, visualized in Figure 1.

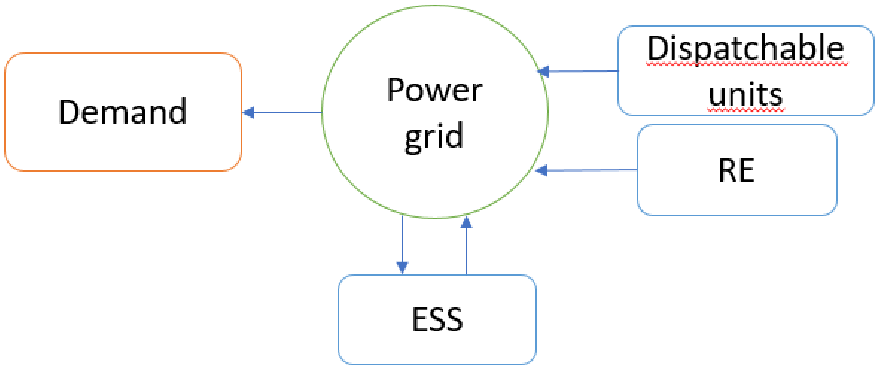

Figure 1. Single-node structure

In other words, the generation units and ESS are assumed directly connected to one single place, ignoring transmission loss. In addition, the demand of the South Korean mainland occurred in the node even if the demand data were collected from different places. Therefore, the power provided by generation units or energy storage is undistinguishable. Any generation unit can supply energy at any time, no matter where the generator is located, the same applies to energy storage.

Such a structure enables us to build a power system model without specific transmission data. Meanwhile, relieves computation burden of the model by simplifying the structure.

3.2.2 Sets, parameters, and variables

The model contains sets as follows (Table 4).

Table 4. Sets of the model

Notation	Definition	Description
t	Time piece in hour	8760 hours in a year
y	Planning Year	Selected 7 years from the range of 2023~2050
g	Dispatchable units	232 dispatchable generators in Korea
co(g)	Coal-fired power plant	Subset of g
lng(g)	LNG-fired power plant	Subset of g
nu(g)	Nuclear power plant	Subset of g
e	ESS technology	Li, PHES, HSS
r	Renewable energy source	Wind and Solar

The time unit is an hour in order to represent renewable energy generation's intermittency and energy storage's charge-discharge behavior. The planning year contains 7 years from 2023 to 2050, to be specific, the year 2023, 2030, 2036, 2040, 2043, 2047, and 2050 are included. In other words, the capacity expansion is allowed only within those 7 years. The rest of the years will have the same amount of capacity as the previous planning year. For instance, the facility capacity of 2048 is the same size as in 2050. Regardless of the model’s planning year, the capacity expansion plan from 2023 to 2036 is fixed by the 10th Basic Plan for Long-term Electricity Supply and Demand.

The parameters are as Table 5 below.

Table 5. Parameters of the model

Notation	Domain	Description	Unit
POI	y	Years from the first year	Year
CcapE	e, y	Projected energy capacity investment cost of ESS	Thousand won/MWh
CpowE	e, y	Projected power capacity investment cost of ESS	Thousand won/MW
CpowRE	r, y	Projected investment cost of renewable generator	Thousand won/MW
Ceff	e	Charging efficiency	%
Deff	e	Discharging efficiency	%
lifeE	e	Service life of ESS technology	year
lifeRE	r	Service life of renewable technology	year
DCtime	e	Discharge time of ESS technology	hour
OMe	e	Annualized fixed maintenance cost of ESS technology	Thousand won/MW
OMvar	e	Variable cost of ESS occurred by discharge	Thousand won/MWh
OMre	r	Annualized fixed maintenance cost of renewable generators	Thousand won/MW-year

Peakcont	r	Capacity factor of renewable generators at peak demand	%
D	y, t	Hourly load	MW
Cfuel	g	Fuel cost of dispatchable generators	Thousand won/MWh
InitialcapE	y, e	Determined energy capacity of ESS in y	MWh
InitialpowE	y, e	Determined power capacity of ESS in y	MW
InitialpowRE	y, r	Determined capacity of renewable energy source in y	MW
SALco	y, (e, r)	Remaining value of RE and ESS installations at the end of the planning horizon in ratio of investment cost	%
AF	t, r	Percentage of renewable power generation to rated capacity	%
Dpcap	y, g	Capacity of Dispatchable units	MW
GHGco	g	Greenhouse gas emission coefficient	CO2kTon/MWh
CO2	y	Limit of CO2 emission each year	CO2kTon/year
Reserve	y	Percentage of required reserve power to year's peak load	MW
Maxload	y	Peak load of year y	MW
rate	-	Interest rate	%

The sources of the parameters are listed in Table 1 and explained in section 3.1. Some parameters relevant to the objective function such as SALco will be explained in the 3.3.1 objective function part.

Table 6. Variables of the model

Notation	Domain	Description	Unit
EpowE	y, e	Capacity expansion of energy storage	MW
EpowRE	y, r	Capacity expansion of renewable generation facility	MW
GD	y, t, g	Electricity generated from dispatchable unit	MW
CRT	y, t, r	Renewable energy curtailed	MWh
GRE	y, t, r	Renewable generation consumed	MWh
Charge	y, t, e	Energy charged in storage	MWh
Discharge	y, t, e	Energy discharged from storage	MWh
SOC	y, t, e	State-of-charge of energy storage	MWh
CurrentRE	y , r	Available rated capacity of renewable generators in year y	MW
CurrentEcap	y, e	Available rated energy capacity of energy storages in year y	MWh
CurrentEpow	y, e	Available rated power capacity of energy storages in year y	MW
TG	y, g	Energy generated by dispatchable sources	MW
REgenerated	y, t, r	Energy generated by renewable sources	MWh
TC	-	Total cost occurred from capacity expansion, operation and maintenance within planning horizon	Thousand won

INV	y	Investment cost occurred in y	Thousand won
OM	y	O&M cost occurred in y including fuel cost	Thousand won
SAL	-	Salvage value of the facilities built within planning horizon	Thousand won
Emission	y, g	Greenhouse gas emission by g in y	CO2 kTon

EpowE and EpowRE are the two main decision variable that represents the capacity expansion decision of renewable energy and energy storage. TC is the objective function of total cost computed from 2023 to 2050, including investment cost and operation & maintenance cost of the generation facilities.

3.3 Equations

The equations for our optimization model is explained in this part, including objective function and constraints. The domains of a parameter or a variable is noted as superscript.

3.3.1 Objective function

$$TC = \sum_{y} [(\frac{1}{1 + rate})^{POI^y} * (INV^y + OM^y)] - SAL \qquad \text{Eq.(3)}$$

The objective function is Eq.(3), which represents the net present(2023) value of the investment cost of the newly built facility and the operation and maintenance cost of the total capacity minus salvage value. The components of the objective function are Eq.(4)~(8).

$$INV^y = \sum_{r} (CpowRE^{r,y} * EpowRE^{r,y}) + \sum_{e} (CpowE^{e,y} * EpowE^{e,y} + EpowE^{e,y} * DCtime^e * Ccap^{e,y}) \qquad \text{Eq.(4)}$$

$$OM^{y} = \sum_{r}(CurrentRE^{y,r} * OMre^{r}) + \sum_{e}(CurrentEpow^{e,y} * OMe^{e} + \sum_{t}(Discharge^{y,t,e} * OMvar^{e}) + \sum_{g} Cfuel^{g} * TG^{y,g}) \quad \text{Eq.(5)}$$

Eq.(4) and (5) are annually computed investment costs and operation & maintenance costs. Investment cost contains the investment cost of renewable energy and energy storage. Energy storage capacity consists of energy capacity and power capacity. As mentioned above, power capacity expansion involves energy capacity expansion. Operation and maintenance cost includes renewable energy and energy storage's fixed annual maintenance cost imposed by the capacity, variable cost of energy storage imposed by the discharged energy within a year, and fuel cost of the dispatchable units. What should be specially noted is that the power capacity expansion of energy storage accompanies energy capacity expansion. The volume of energy expansion is power capacity expansion multiplied by the discharge time of the storage technology.

$$SAL = \sum_{y,r} SALco^{r,y} * CpowRE^{y,r} * EpowRE^{y,r} + \sum_{y,e} SALco^{e,y} * (CpowE^{e,y} * EpowE^{e,y} + EpowE^{e,y} * DCtime^{e} * Ccap^{e,y}) \quad \text{Eq.(6)}$$

Without a salvage cost refund, the model is reluctant to make investments at the end of the model year for the advantage gained from the facility is less than the investment cost. The salvage value (Eq.(6)) is computed by multiplying the salvage coefficient (Eq.(7)) with the investment cost for individual technologies.

$$SALco^{(e,r),y} = \frac{1}{(1 + rate)^{ord(y)}} * \frac{Remaining\ life}{life^{(e,r)}} \quad \text{Eq.(7)}$$

As shown in Eq.(7), the salvage coefficient denotes the present value of the remaining value in comparison to the investment cost when a capacity expansion happens in year y. The salvage coefficient increases linearly if remaining life is longer, in other words, built near the end of the planning horizon, which is called the straight-line depreciation method. The remaining life is the remaining lifespan of a facility in 2050 if built in year y (Eq.(8)). Studies by Jang et al.(2013), Zhang et al.(2022), Alsharif et al.(2016) and Schmidt et al.(2019) supposed that zero value remains at the end of the lifespan and this study applies the same.

$$Remaining\ \ life = \max[0, life^{(e,r)} - (2050 - y)] \qquad \text{Eq.(8)}$$

3.3.2 Constraints

Eq. (9)~(23) are constraints. They are used to guide generators and storages to work properly and restrain the value of variables to a limit.

The Eq.(9) is a power balance constraint, that keeps the net power in the grid greater than demand every hour of the planning years. The power demand is primarily met by supply from dispatchable and renewable units. If the demand is unmet, the shortage can be made up by discharging the energy storage. Similarly, if the supply exceeds the demand, the energy storage can store the energy in preparation for future use. Eq.(9) uses the equality sign rather than the greater sign to let renewable generators curtail the surplus power generation.

$$D^{y,t} = \sum_{g} GD^{y,t,g} + \sum_{r} GRE^{y,t,r} + \sum_{e} (Discharge^{y,t,e} - Charge^{y,t,e}) \qquad \text{Eq.(9)}$$

Eq.(10) and (11) are emission constraint that limits the annual carbon dioxide emission under $CO2^{y}$. Particularly, the emission limit in 2050 is set to 0 so that South Korea will achieve zero emissions in the power sector.

$$Emission^{y,g} = GHGco^{g} * TG^{y,g} \quad \text{Eq.(10)}$$

$$\sum_{g} Emission^{y,g} \leq CO2^{y} \quad \text{Eq.(11)}$$

Eq.(12) and (13) are constraint for dispatchable units. Eq.(12) limits the output of a unit's upper bound to its capacity. Eq.(13) defines the total generation of a unit within year y.

$$GD^{y,t,g} \leq DPcap^{y,g} \quad \text{Eq.(12)}$$

$$TG^{y,g} = \sum_{t} GD^{y,t,g} \quad \text{Eq.(13)}$$

Eq.(14) and (15) are for renewable energy. Eq.(14)'s shows that the actually supplied renewable energy equals to renewable energy generation subtracted by curtailed power. Eq.(15) reveals how the model yields the output of renewable energy.

$$GRE^{y,t,r} = REgenerated^{y,t,r} - CRT^{y,t,r} \quad \text{Eq.(14)}$$

$$REgenerated^{y,t,r} = AF^{t,r} * CurrentRE^{y,r} \quad \text{Eq.(15)}$$

The reserve constraint is Eq.(16). It represents the total generated power must be greater than the peak load multiplied by reserve margin.

$$\sum_{g} DPcap^{y,g} + \sum_{r} (Peakcont^{r} * CurrentRE^{y,r}) \geq (1 + Reserve) * Maxload^{y} \quad \text{Eq.(16)}$$

The following equations(Eq.(17)~(20)) are relevant to energy storage. The State-of-Charge (SoC) shift to the next period and its upper limit is defined as below. Additionally, the charging and discharging speed are also restrained.

$$OC^{y,t,e} = SOC^{y,t-1,e} + Ceff * Charge^{y,t,e} - Deff * Discharge^{y,t,e} \quad \text{Eq.(17)}$$

$$SOC^{y,t,e} \leq CurrentEcap^{y,e} \quad \text{Eq.(18)}$$

$$Charge^{y,t,e} \leq CurrentEpow^{y,e} \quad \text{Eq.(19)}$$

$$Discharge^{y,t,e} \leq CurrentEpow^{y,e} \quad \text{Eq.(20)}$$

Lastly, Eq.(21)~(23) are to calculate the remaining available capacity in y. The facility which expired its utility lifespan is excluded from the current capacity.

$$CurrentRE^{y,r} = InitialpowRE^{r,y} + \sum_{y'-lifeRE+1}^{y} EpowRE^{y',r} \quad \text{Eq.(21)}$$

$$CurrentEpow^{y,e} = InitialpowE^{e,y} + \sum_{y'-lifeE+1}^{y} EpowE^{y',r} \quad \text{Eq.(22)}$$

$$CurrentEcap^{y,e} = InitialcapE^{e,y} + \sum_{y'-lifeE+1}^{y} (DCtime^{e} * EpowE^{y',r}) \quad \text{Eq.(23)}$$

Except for the numbered constraints, all the variables are positive.

3.4 Scenario setting

The scenario setting for this study is displayed in Table 7.

Table 7. Scenario description

Scenario	Description
Scenario 1 (Benchmark)	Renewable energy is optimized prior to the ESS, then optimize ESS under renewable energy optimization result
Scenario 2	Co-optimize renewable energy and ESS
Scenario 3	Based on scenario 2, accelerate technology development of ESS 15%p
Scenario 4	Based on scenario 2, decelerate technology development of ESS 15%p

The scenario 1 is a benchmark scenario, which would firstly optimize the renewable energy to determine its capacity expansion plan, then energy storage expansion plan is made under the renewable energy expansion plan. This roughly represents the capacity planning process of the Korea Government that installing renewable energy prior to the energy storage planning. The scenario 2 is the planning method proposed in this study which sets both the renewable energy and ESS expansion as decision variables.

Depending on this study's aim to emphasize the need of co-optimization of renewable energy and energy storage, scenario 1 and scenario 2 are organized. Scenario 3 and 4 are accelerated/decelerated development of ESS technology. The technology development is represented as the speed of cost diminution over time. The comparison will be made among the result of scenario 2, 3, and 4, for scenario 2 has the original technology development speed as predicted by Schmidt et al. (2019). Scenario 3 and 4 can also be considered as a sensitivity test of the ESS unit cost change to the result.

Chapter 4. Results

4.1 Main result

4.1.1 Total cost

The result of the total cost is shown in Table 8, and Figure 2.

Table 8. Total cost from 4 scenarios

Scenario	Total cost (hundred trillion won)
Scenario 1 (Benchmark)	7.18
Scenario 2	4.59
Scenario 3	4.18
Scenario 4	4.72

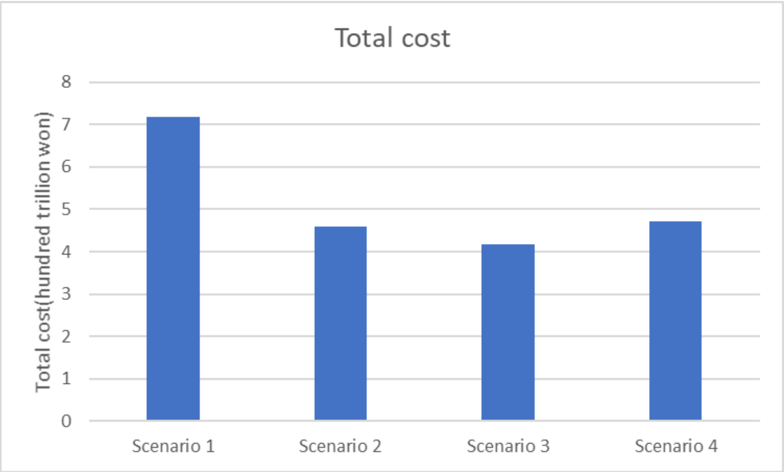

Figure 2. The total cost of 4 scenarios

The total cost is the aggregated cost of the power sector's facility investment cost and operation and maintenance cost in achieving net-zero by 2050. The cost efficiency of scenario 1 is 56% lower than the scenario 2, namely, the separated optimization has worse cost efficiency than co-optimization. In scenario 1, it is forced to reach zero emission by 2050 without planning ESS. The shortage of storage capacity aroused the inefficiency for the grid flexibility is not secured. There is no doubt that the accelerated scenario (scenario 3) would yield the lowest total cost, and vice versa. The sensitivity of the cost-decreasing speed to the total cost is 53.3% and 18.7% when accelerated and decelerated, respectively.

4.1.2 ESS capacity expansion

Optimized power capacity of energy storage in 2050 is as follows (Table 8).

Table 9. Power capacity of energy storage in 2050

Scenario	Li(GW)	PHES(GW)	HSS(GW)	Total(GW)
Scenario 1 (Benchmark)	0	7.8	0	7.8
Scenario 2	31	12	48	92
Scenario 3	524	6.5	0	530
Scenario 4	15	12.8	41	70

Table 9 is visualized in Figure 3.

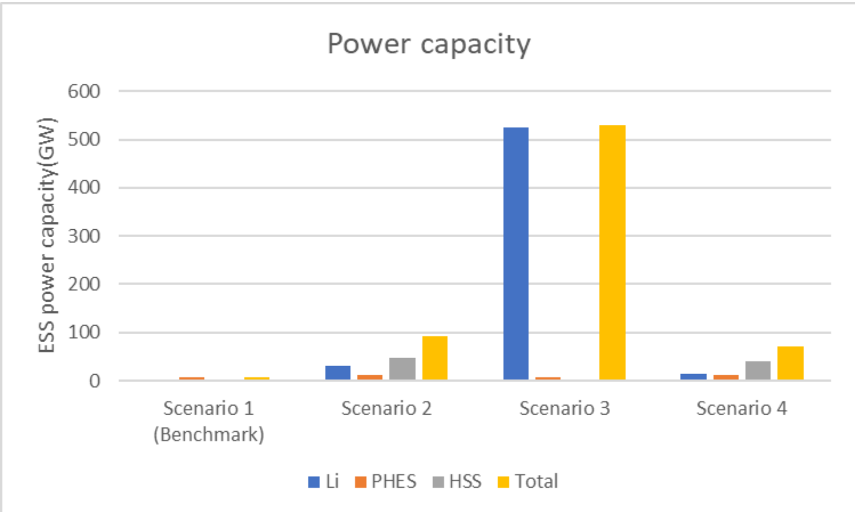

Figure 3. Power capacity of ESS

In scenario 1, the initial capacity of the lithium battery faded but not installing more. The PHES expansion in 2047 is the only storage expansion in scenario 1. This is because in scenario 1, we forced it to attain zero emission without considering additional ESS installation in the first stage. Though we allowed expanding capacity afterward, it could not find the advantage installing spending more expenditure after being able to meet the demand with renewable energy, nuclear power, and 7.8 GW of PHES. Scenario 2 has installed 11.8 times more storage than scenario 1. We can see that scenario 3 installed 524 GW of lithium battery, 17 times of scenario 2, 5.8 times in total power capacity. The cost reduction speed seems contributed to this result because lithium has the fastest cost reduction, moreover, accelerated reduction rate has more effect on the Li that the power cost of the lithium battery ESS in scenario 3 is merely 7.8% of that in scenario 2 and it is the cheapest of all ESS technologies. The overwhelming cost competitiveness of Li has it dominate the ESS share in scenario 3. On the contrary, scenario 4's installation of lithium is even lower than scenario 2, and HSS reappeared. The reason for this result has in common with the previous one. The price competitiveness of lithium ESS is been damaged by slowed down development speed. On the other hand, the HSS, whose cost reduction is slower than lithium gained relative superiority to the lithium battery.

Table 9 and Figure 4 visualize the energy capacity of ESS technologies in 2050.

Table 10. Energy capacity of energy storage in 2050

Scenario	Li(GW)	PHES(GW)	HSS(GW)	Total(GW)
Scenario 1 (Benchmark)	0	60	0	60
Scenario 2	186	97	1864	2148
Scenario 3	3146	49	0	3196
Scenario 4	91	97	1624	1813

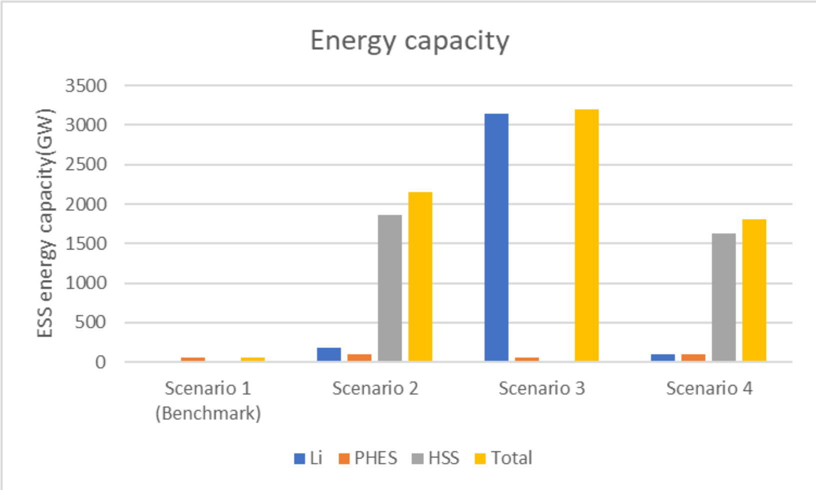

Figure 4. The energy capacity of ESS

The total capacity of scenario 3 shrinks from 5.8 times of scenario 2 to 1.5 times in the case of energy capacity. The lithium battery storage is higher than the HSS in other scenarios, which signifies the lithium in scenario 3 plays the role of long-term ESS as well as short-term's.

4.1.3 Renewable energy capacity expansion

Table 11 and Figure 5 illustrate the optimal renewable generation capacity of scenarios in 2050.

Table 11. Renewable energy capacity in 2050

Scenario	Wind(GW)	Solar(GW)	Total(GW)
Scenario 1 (Benchmark)	1219	315	1534
Scenario 2	118	501	619
Scenario 3	122	304	426
Scenario 4	117	555	672

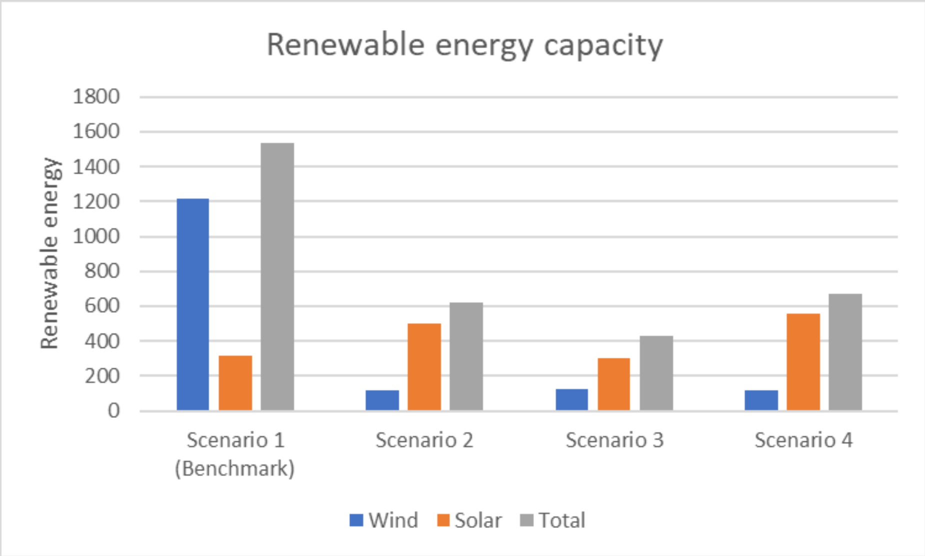

Figure 5. Capacity of renewable energy

As expected, scenario 1 installed the most renewable energy and the size of the total capacity reaches 2.5 times of scenario 2. We can conclude that the result of scenario 1 is the required renewable energy capacity under no additional ESS expansion for 2050 net-zero. Combining with the result of ESS capacity, we can find that in the case that renewable energy plans and ESS are optimized together (scenario 2, 3, 4), they tend to expand solar power rather than wind power for it is cheaper in LCOE. On the contrary, it tends to install wind power for its fluctuation is less than solar power (scenario 1). Moreover, without LNG power plant and sufficient energy storage, scenario 1 needs to fulfill the net load only by renewable energy source.

From the comparison of scenario 2, 3 and 4 we can identify the technology development speed does matter. Scenario 3 installed less than scenario 2, and scenario 4 installed more. This is because in scenario 3, securing sufficient storage capacity is easier than scenario 2, and harder in scenario 4. Thus, the difference in technology development provokes the difference in energy storage capacity, moreover, makes the renewable energy capacity vary.

4.1.4 Curtailed energy

The curtailed energy is the surplus power generated by renewable generators and wasted. The specific quantity in 2050 is listed in Table 12 and Figure 6.

Table 12. Curtailed energy and curtailment ratio

Scenario	Wind(TW)	Solar(TW)	Total(TW)	Wind(%)	Solar(%)
Scenario 1 (Benchmark)	1812	535	2348	79.8%	99%
Scenario 2	50	262	313	15%	31%
Scenario 3	41	133	175	16%	24%
Scenario 4	68	350	418	18%	38%

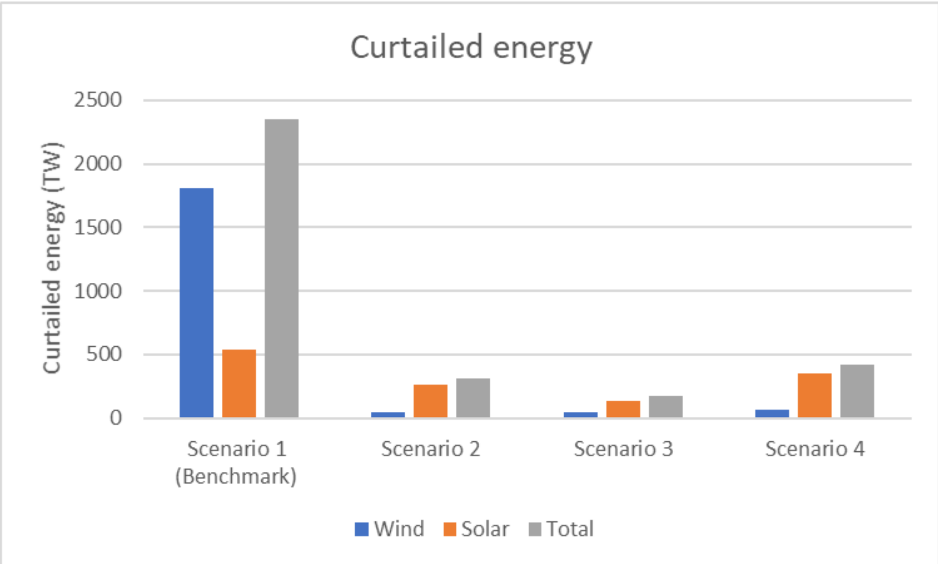

Figure 6. Curtailed energy in 2050

The curtailed energy in scenario 1 is noticeably higher than in any other scenario. Renewable energy capacity planned without considering ESS has to curtail the 79.8% of the wind generation and 99% of the solar generation at the end of the planning horizon. Despite the wind curtailment is higher than solar curtailment, the curtailment ratio of wind is lower. Understandably, the faster ESS technology development, the less curtailed energy.

4.2 Scenario-specific results

In section 4.2, more specific results from each scenario will be presented.

The power mix result of 4 scenarios turns out to be similar to each other. Because the binding constraint of renewable energy expansion is emission constraint which applies identically to all the scenarios. The power mix is as Figure 7.

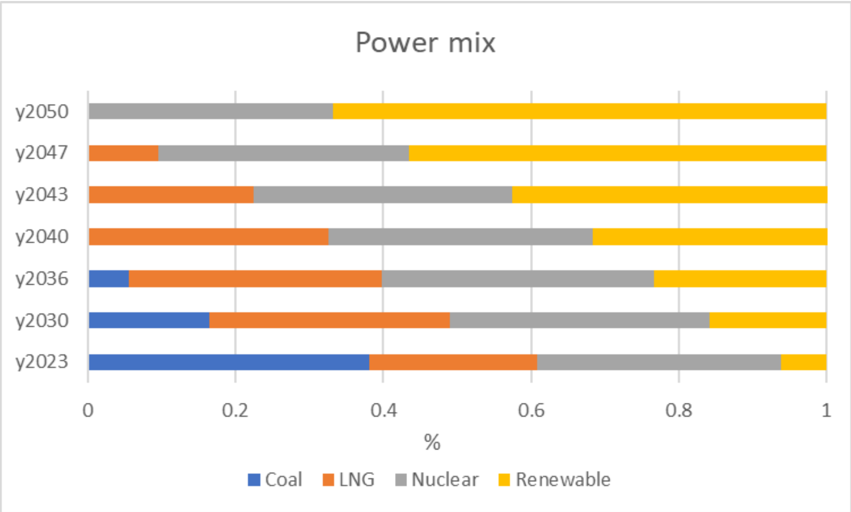

Figure 7. Power mix

The coal-fired power plant stops running after 2036 and LNG power plant stops after 2047. The share of nuclear power is steady since the nuclear power plant's capacity is fixed after 2036 and the generation pattern is also fixed. Notably, renewable energy has to be in charge of 66.8% of the load in 2050.

4.2.1 Scenario 1

Scenario 1 sequentially optimizes the renewable energy and then the energy storage. In other words, it meets zero emission requirement without energy storage expansion in the first stage of optimization. Therefore, unless charging a penalty cost on curtailed energy, energy storage is not necessary in the second stage.

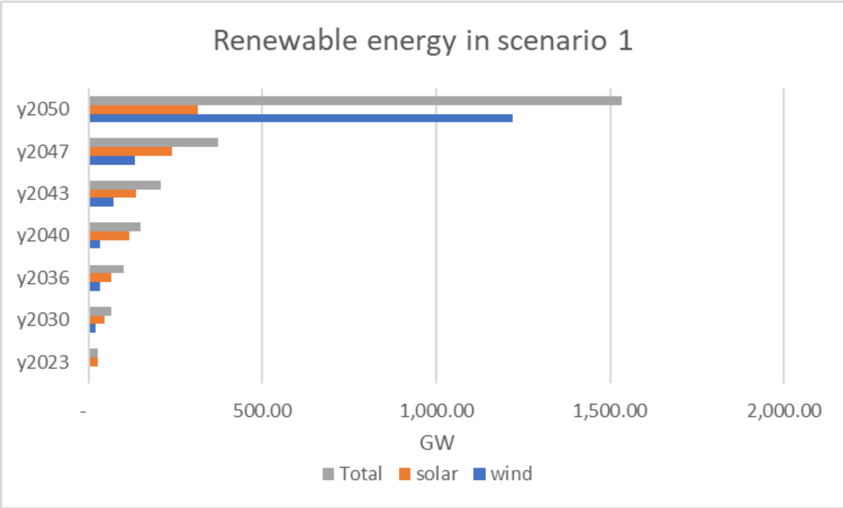

Figure 8. Cumulative renewable energy capacity

The renewable energy expansion result over time in scenario 1 is as above (Figure 7). It is significant that the total renewable energy capacity undergoes a drastic increase in 2050 when all the coal and LNG power plants stop operating. As long as LNG power plant in this model can change the output in no time, it can be said that the LNG power plant functions as a flexible resource, supplements unmet demand due to the output fluctuation of renewable energy. Consequently, reduces the demand for renewable energy facilities.

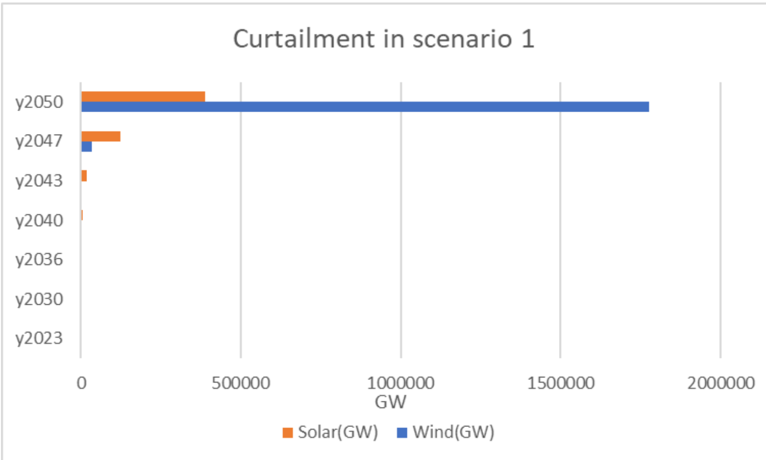

Figure 9. Annual curtailment in scenario 1

As seen in Figure 9, the curtailment was not significant before 2043, since the dramatic rise of renewable energy capacity takes place in 2050.

4.2.2 Scenario 2

The energy and power capacity of ESS in scenario 2 is as below (figure 10, 11).

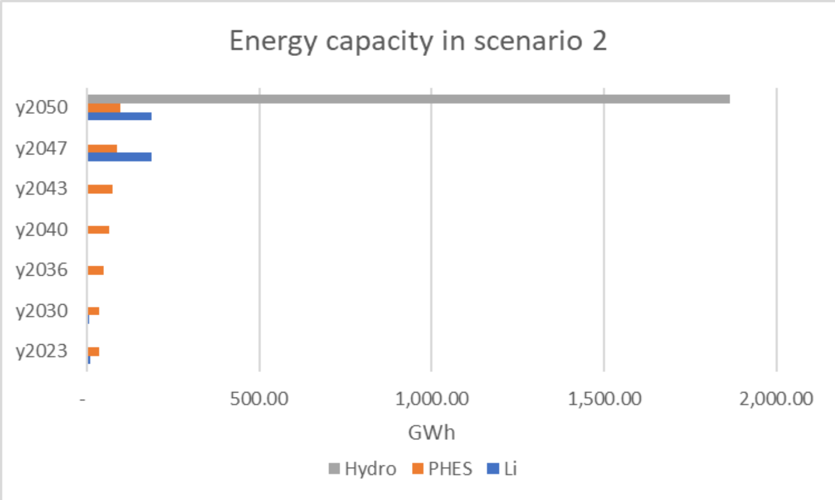

Figure 10. Cumulative Energy capacity in scenario 2

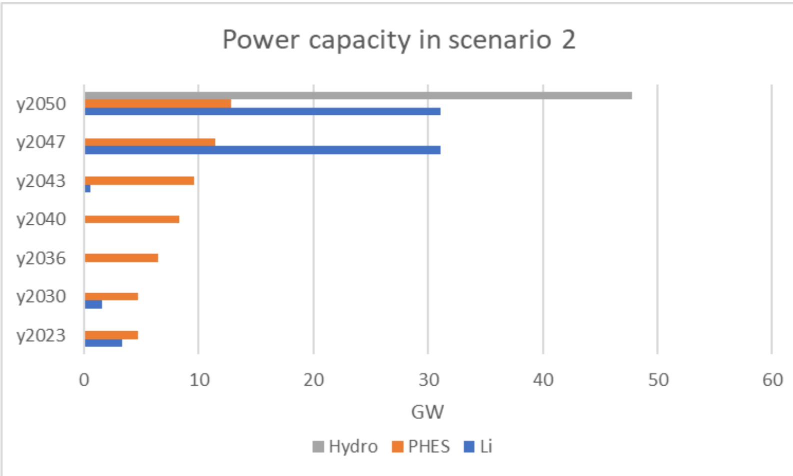

Figure 11. Cumulative power capacity in scenario 2

It shows that the HSS, which is the cheapest in energy expansion and the costliest in power expansion, overwhelms other alternatives in both sizes in 2050. PHES is continuously installing at its maximum capacity allowed in each expansion period, whereas the Li extended only in 2043 and 2047.

The maximum power output that ESS should be responsible for in 2050 is 79.15 GW (8 AM, December 20th), but the model expanded 91.7 GW in total. In 2050, the maximum SoC of HSS reached its energy capacity. Therefore, it can be said that the power system requires energy capacity rather than power capacity in 2050.

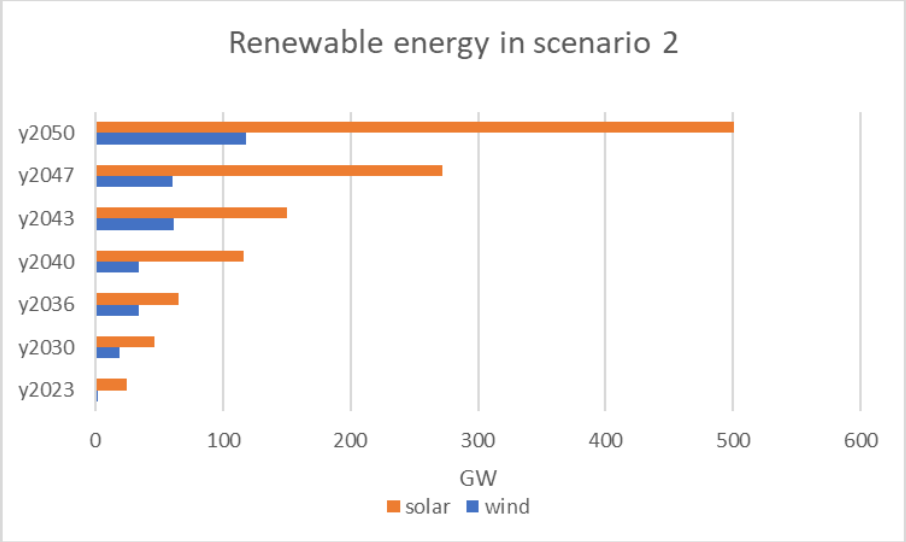

Figure 12. Cumulative renewable energy in scenario 2

Contrary to scenario 1, the major renewable energy source is solar power, which is cheaper in LCOE. Scenario 2 can secure sufficient energy storage by co-optimization. mitigate the fluctuation of solar energy, and allows the system to introduce a bulk of solar energy.

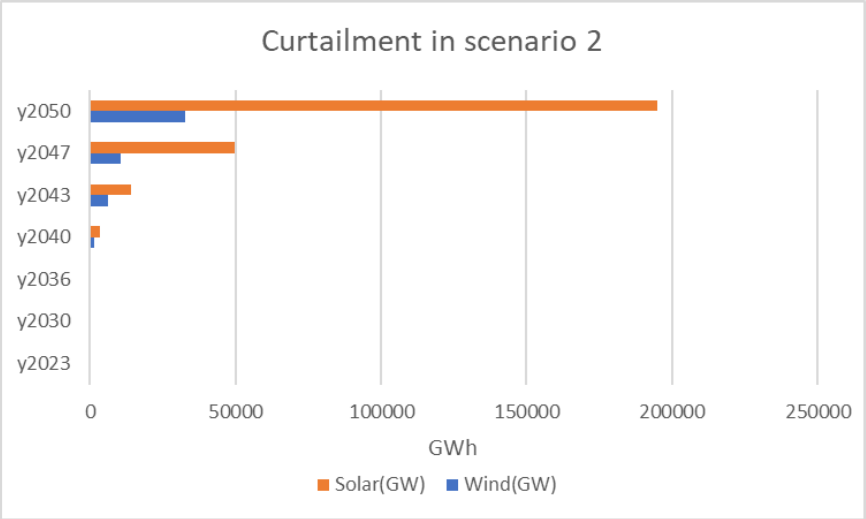

Figure 13. Annual curtailment in scenario 2

Figure 13 illustrates the annual curtailment in scenario 2. According to the power mix, the share of renewable energy increased by 10% from 2047 to 2050 but installed 86% more renewable facilities. The excessive installation induced the rise of curtailment and curtailment ratio.

4.2.3 Scenario 3

The difference between scenario 3 from scenario 2 is that the unit cost of ESS technology drops 15% more rapidly, as shown in Figures 14 and 15.

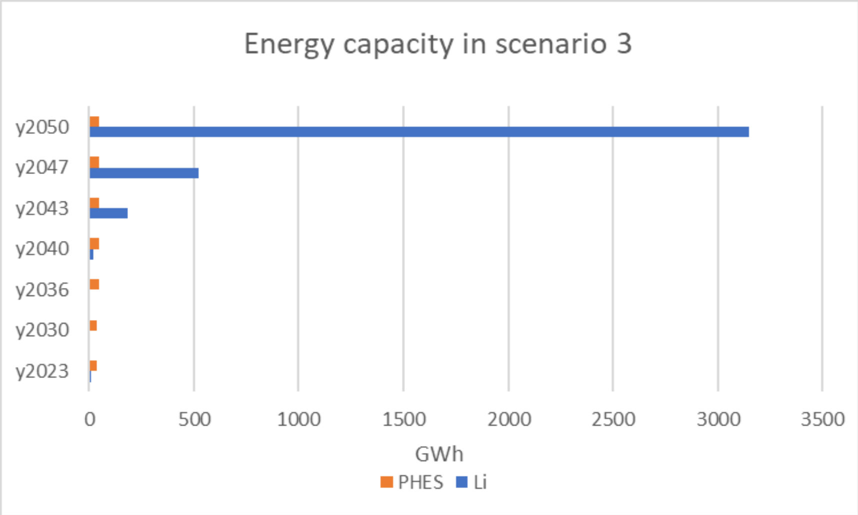

Figure 14. Cumulative Energy capacity in scenario 3

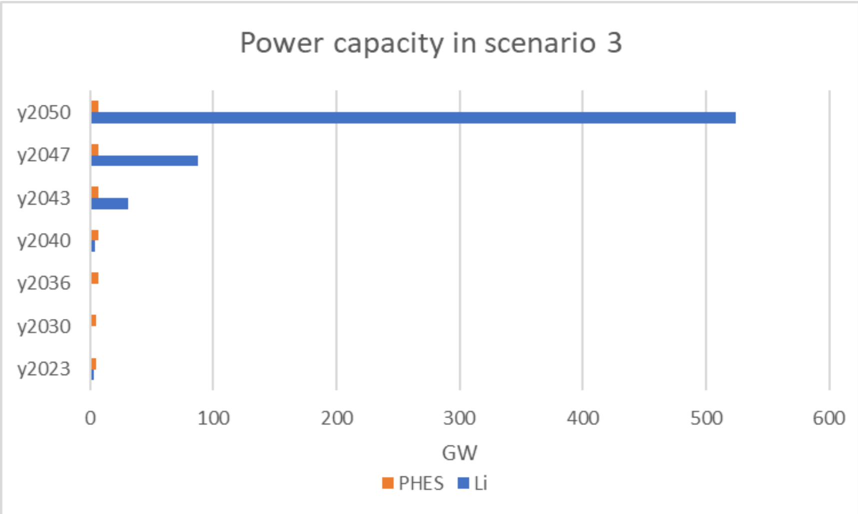

Figure 15. Cumulative power capacity in scenario 3

The result in scenario 3 is lopsided that Li takes over the share of 98.3% of the entire storage power capacity. Enhanced technology development has dramatically reduced lithium battery's unit cost even though unit energy cost is only 124% of HSS when unit power cost is merely 0.6% of the HSS. Moreover, Li's round-trip efficiency is 0.86, which is 215% of HSS. Thus, the dominating position of lithium is reasonable in scenario 3.

The result shows that the power capacity is 500% of that in scenario 2, but the energy capacity is 150% of scenario 2. Since the load is identical in 4 scenarios, procuring the energy capacity is a higher priority than power capacity.

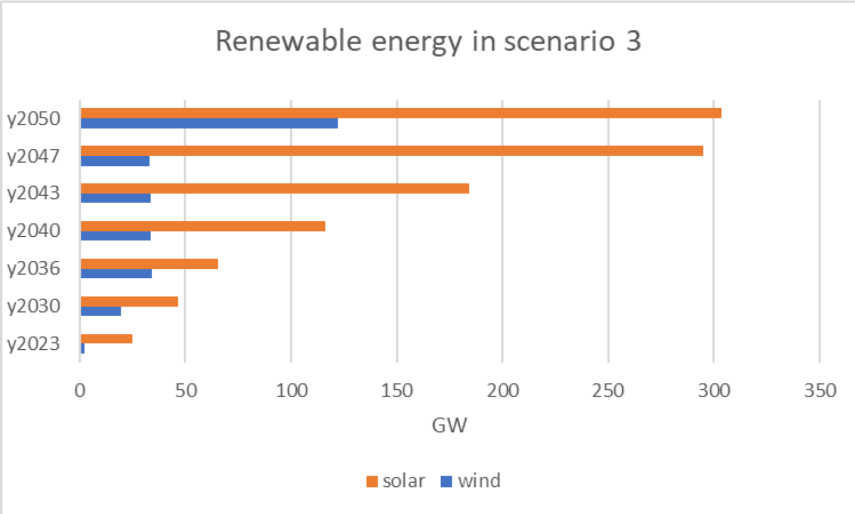

Figure 16. Cumulative renewable energy in scenario 3

Figure 16 displays the cumulative renewable energy of scenario 3. The wind power capacity is 3% more than scenario 2, but the solar power capacity is reduced by 40%, consequently, the total renewable energy capacity is diminished by 31% from scenario 2. The reason can be found in figure 14 and 15, that total installed ESS capacity increased with the enhanced cost-reduction speed.

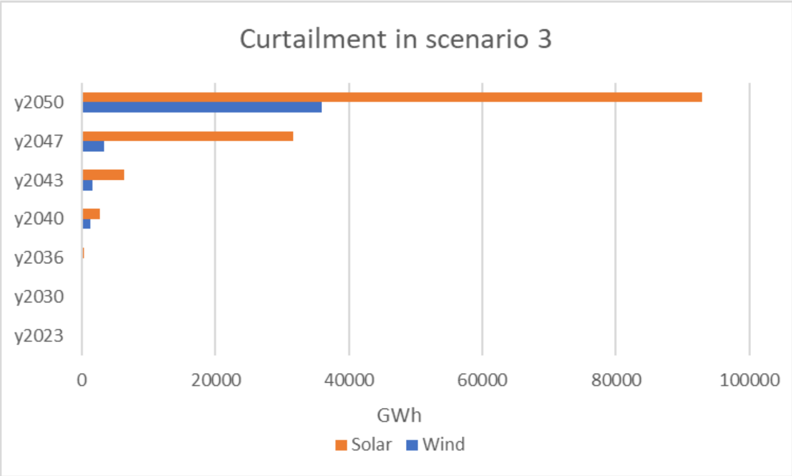

Figure 17. Annual curtailment in scenario 3

As Figure 17 depicts, the curtailment pattern over time is not much different from the scenario 2, but the scale is reduced in half.

4.2.4 Scenario 4

Scenario 4 is the opposite of scenario 3, the unit cost of ESS technology decreases 15% slower. Figure 18 and 19 presents the ESS expansion result of scenario 4.

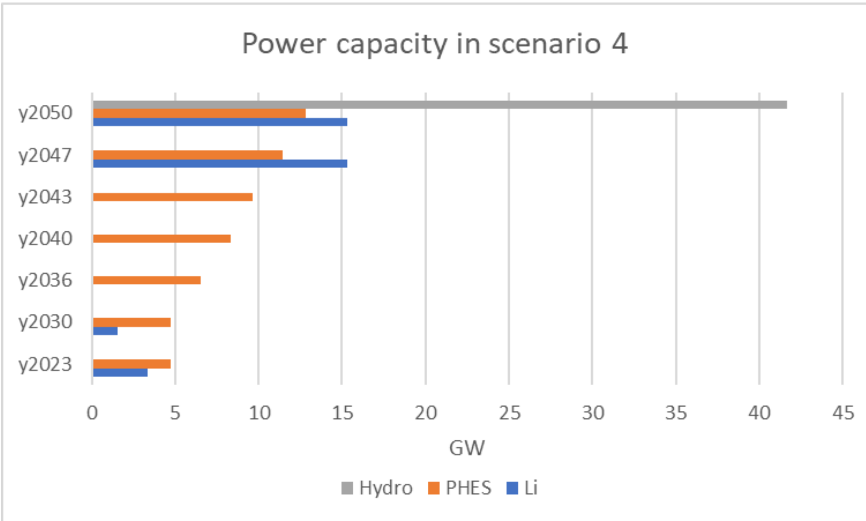

Figure 18. Cumulative Energy capacity in scenario 4

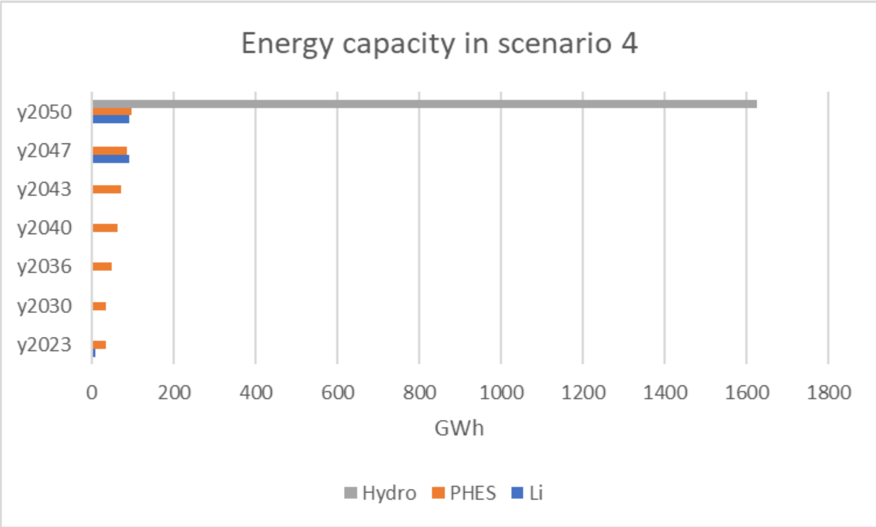

Figure 19. Cumulative power capacity in scenario 4

Unlike scenario 3, HSS appeared in 2050 since the Li became less attractive due to the cost reduction rate diminution. For the same reason, the total energy capacity is 21% lower than scenario 2 and 23% lower in power capacity.

The cumulative renewable energy capacity is shown below (Figure 20).

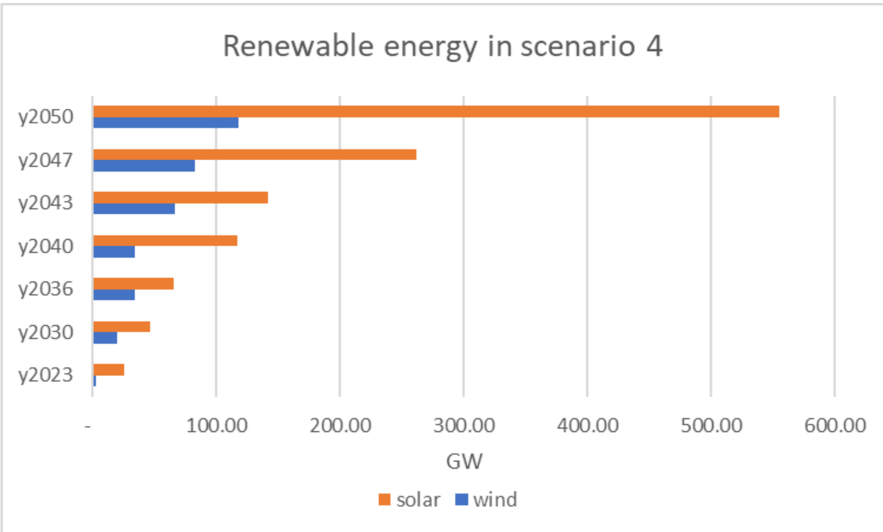

Figure 20. Cumulative renewable energy in scenario 4

Due to the higher unit price of ESS, its capacity is harder to obtain. And as a result, the total renewable energy capacity increased by 9% by comparison with scenario 2.

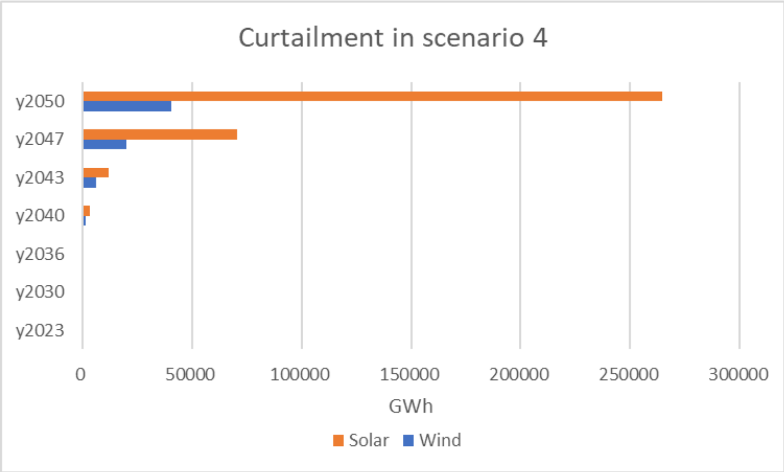

Figure 21. Annual curtailment in scenario 4

The annual curtailment in scenario 4 is displayed in Figure 21. The overall curtailment is higher than scenario 2 and 3.

Chapter 5. Conclusion and discussion

This study sought to argue the need for simultaneous optimization in the planning of renewable energy and ESS facilities for South Korea. Moreover, in one hand, we have set the operation time unit as 1 hour and it enabled realistic emulation of renewable energy sources' fluctuating output and charge & discharge operation of energy storage. On the other hand, the impact of technology development speed of energy storage on optimal facility planning and its efficiency is explored additionally.

The result shows that the co-optimizing is required in capacity expansion planning in order to reduce the total cost of achieving 2050 net-zero. And also can decrease the energy loss caused by the renewable energy curtailment. In addition, the co-optimized scenario requires less renewable generation facility than the one-by-one scenario. By comparing the scenario 1 and 2, we can identify that the existence of ESS alters the type of renewable energy which is mainly utilized. That is to say, when ESS technology is not allowed to expand when planning renewable energy, wind power becomes the main energy source that supplies energy. On the contrary, solar power prevails over wind power when ESS is optimized together.

The technology development speed is another key research object in this study. The development speed of energy storage firstly affects the unit price, and then the superior technology alternatives. Furthermore, the relationship of price competitiveness among ESS technologies varies over time. As shown in the result part, the scenario 3's lithium battery storage takes 98.3% of the total power capacity for it is the cheapest alternative in the whole planning horizon. However, in scenario 2 and 4, the HSS occupies the largest share. The HSS is built at the end of the planning horizon in both scenarios. Before then, lithium battery and PHES expanded.

Here are some policy implications. According to the result, the effectiveness of co-optimization in long-term planning is proven. Therefore, the planning of electric power facilities should be considered simultaneously. Carefully investigated, it can be seen that the renewable energy capacity drastically increases from 2047 to 2050 when the LNG power plant ceases operating. Switching the power output is not a considerable option for the nuclear power plant, the LNG is the only dispatchable technology that can run flexibly. Thus, the operation of LNG plants lowers the demand for renewable energy capacity. At this point, it can be said that combining LNG generators and CCUS (Carbon Capture Utilization and Storage) to achieve carbon neutrality is worth considering when renewable energy and ESS capacity are not well-secured.

From the perspective of technology development, acceleration is needed to reduce the total cost. Furthermore, the reduced unit cost of ESS leads to sufficient ESS capacity, and then to less demand for renewable energy sources. Meanwhile, according to scenario 2, 3 and 4, the HSS starts implemented in the grid at the end of the planning horizon. It is 10 years later than the plan of the Korean Government (“Roadmap to activate hydrogen economy”, 2019) that plans to procure 15GW of the Hydrogen fuel cell. Thus, investing in hydrogen technology is necessary to meet the goal.

Some limitations exist as follows. Firstly, we could not manage to allow capacity expansion in all planning years due to the computation issue. This could result in significant inefficiency in expansion planning and unrealistic result. Secondly, except for the technology development speed, there are still several factors that contain uncertainty but are not addressed in the current study such as demand projection or types of energy storage. Thirdly, despite the curtailment of renewable energy could cause energy loss (Hashemi & Østergaard., 2017), financial loss (Porkar et al., 2011), and low grid operation efficiency (Kim et al., 2020), the penalty of the curtailment is not applied to the model. And also, we only studied wind and solar energy as renewable energy sources, when other sources such as fuel cells or hydropower are already in the plan of the Government (2023). Lastly, the energy facility planning by the government is not always conducted through the cost minimization perspective. To apply more realistic and reasonable planning, further considerations need to be made.

We have future work recommendations. From the result of the first scenario, the ESS gains no advantages introduced after planning renewable energy capacity by priority. However, if the penalty cost of the curtailment had been considered in the model, the ESS facility will be come in handy even if planned in the second order. Additionally, the total cost would be different from the current result when penalizing the curtailment.

Bibliography

Asensio, M., Muñoz-Delgado, G., & Contreras, J. (2017). Bi-level approach to distribution network and renewable energy expansion planning considering demand response. IEEE Transactions on Power Systems, 32(6), 4298-4309.

Bartolini, A., Carducci, F., Muñoz, C. B., & Comodi, G. (2020). Energy storage and multi energy systems in local energy communities with high renewable energy penetration. Renewable Energy, 159, 595-609.

Bistline, J., Blanford, G., Mai, T., & Merrick, J. (2021). Modeling variable renewable energy and storage in the power sector. Energy Policy, 156, 112424.

Chen, H., Chen, J., Han, G., & Cui, Q. (2022). Winding down the wind power curtailment in China: What made the difference?. Renewable and Sustainable Energy Reviews, 167, 112725.

da Luz, T., & Moura, P. (2019). Power generation expansion planning with complementarity between renewable sources and regions for 100% renewable energy systems. International Transactions on Electrical Energy Systems, 29(7), e2817.

Dagoumas, A. S., & Koltsaklis, N. E. (2019). Review of models for integrating renewable energy in the generation expansion planning. Applied Energy, 242, 1573-1587.

Gantz, J. M., Amin, S. M., & Giacomoni, A. M. (2012, September). Optimal mix and placement of energy storage systems in power distribution networks for reduced outage costs. In 2012 IEEE Energy Conversion Congress and Exposition (ECCE) (pp. 2447-2453). IEEE.

Government of Korea. (2020). Submission under the Paris Agreement The Republic of Korea's Update of its First Nationally Determined Contribution (In Korean).

Government of Korea. (2021). Enhanced update of the First Nationally Determined Contribution (NDC) (In Korean).

Government of Korea. (2021). 2050 Carbon neutrality scenario (In Korean).

Government of Korea. (2023). 1st Basic Plan of National Eco-friendly Development

Haas, J., Cebulla, F., Nowak, W., Rahmann, C., & Palma-Behnke, R. (2018). A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply. Energy Conversion and Management, 178, 355-368.

Hashemi, S., & Østergaard, J. (2017). Methods and strategies for overvoltage prevention in low voltage distribution systems with PV. *Iet Renewable Power Generation*, *11*(2), 205–214. https://doi.org/10.1049/iet-rpg.2016.0277

Huh, S. Y., & Lee, C. Y. (2014). Diffusion of renewable energy technologies in South Korea on incorporating their competitive interrelationships. Energy Policy, 69, 248-257.

Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—Characteristics and comparisons. Renewable and sustainable energy reviews, 12(5), 1221-1250.

Javadi, M. S., Lotfi, M., Gough, M., Nezhad, A. E., Santos, S. F., & Catalao, J. P. (2019, June). Optimal spinning reserve allocation in presence of electrical storage and renewable energy sources.

In 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-6). IEEE.

Jeon, W., & Lee, C. Y. (2019). Estimating the cost of solar generation uncertainty and the impact of collocated energy storage: The case of Korea. Sustainability, 11(5), 1389.

Kim, R., Wang, Y., Vudata, S. P., Bhattacharyya, D., Lima, F. V., & Turton, R. (2020). Dynamic optimal dispatch of energy systems with intermittent renewables and damage model. *Mathematics*, *8*(6), 868.

Lee, Y. H., Jeong, I. W., & Sung, T. H. (2021). An Assessment of the Optimal Capacity and an Economic Evaluation of a Sustainable Photovoltaic Energy System in Korea. Sustainability, 13(21), 12264.

Li, M., Shan, R., Virguez, E., Patiño-Echeverri, D., Gao, S., & Ma, H. (2022). Energy storage reduces costs and emissions even without large penetration of renewable energy: The case of China Southern Power Grid. Energy Policy, 161, 112711.

Li, Q., Wang, J., Zhang, Y., Fan, Y., Bao, G., & Wang, X. (2020). Multi-period generation expansion planning for sustainable power systems to maximize the utilization of renewable energy sources. Sustainability, 12(3), 1083.

Min, D., Ryu, J., & Choi, D. (2017). A long-term capacity expansion planning model for an electric power system integrating large-size renewable energy technologies. Computers & Operations Research, 96, 244–255. https://doi.org/10.1016/j.cor.2017.10.006

Ministry of Trade, Industry and Energy. (2020).The Fifth Basic Plan for New and Renewable energy Development, Utilization and Supply (In Korean)

Ministry of Trade, Industry and Energy. (2020). The 9th Basic Plan for Long-term Electricity Supply and Demand (BPE) (In Korean)

Ministry of Trade, Industry and Energy. (2023). The 10th Basic Plan for Long-term Electricity Supply and Demand (BPE) (In Korean). 2023-1-13.

Ministry of Trade Industry and Energy. (2019). Press releases: Roadmap to activate hydrogen economy.
http://www.motie.go.kr/motie/py/td/tradefta/bbs/bbsView.do?bbs_cd_n=72&cate_n=3&bbs_seq_n=210222

Oh, H., Hong, I., & Oh, I. (2021). South Korea’s 2050 carbon neutrality policy. East Asian Policy, 13(01), 33-46.

Park, M., Barrett, M., & Cassarino, T. G. (2019). Assessment of future renewable energy scenarios in South Korea based on costs, emissions and weather-driven hourly simulation. Renewable Energy, 143, 1388–1396. https://doi.org/10.1016/j.renene.2019.05.094

Park, S., Yun, B. H., Yun, C., Lee, D. H., & Choi, D. (2016). An analysis of the optimum renewable energy portfolio using the bottom–up model: Focusing on the electricity generation sector in South Korea. Renewable & Sustainable Energy Reviews, 53, 319–329. https://doi.org/10.1016/j.rser.2015.08.029

Porkar, S., Abbaspour-Tehrani-fard, A., Poure, P., & Saadate, S. (2011). Distribution system planning considering integration of distributed generation and load curtailment options in a competitive electricity market. *Electrical Engineering*, *93*, 23-32.

Rajesh, K., Bhuvanesh, A., Kannan, S., & Thangaraj, C. (2016). Least cost generation expansion planning with solar power plant using differential evolution algorithm. Renewable Energy, 85, 677-686.

Samuel, A., Krishnamoorthy, M., Ananthan, B., Subramanian, K., & Murugesan, K. P. (2022). Application of metaheuristic algorithms for solving real-world electricity demand forecasting and generation expansion planning problems. Iranian Journal of Science and Technology, Transactions of Electrical Engineering, 46(2), 413-439.

Sani, S. B., Celvakumaran, P., Ramachandaramurthy, V. K., Walker, S., Alrazi, B., Ying, Y. J., ... & Rahman, M. H. A. (2020). Energy storage system policies: Way forward and opportunities for emerging economies. Journal of Energy Storage, 32, 101902.

Schmidt, O. G., Melchior, S., Hawkes, A., & Staffell, I. (2019b). Projecting the Future Levelized Cost of Electricity Storage Technologies. Joule, 3(1), 81–100. https://doi.org/10.1016/j.joule.2018.12.008

Spataru, C., Kok, Y. C., Barrett, M., & Sweetnam, T. (2015). Techno-economic assessment for optimal energy storage mix. Energy Procedia, 83, 515-524.

Teske, S., Pregger, T., Simon, S., & Naegler, T. (2018). High renewable energy penetration scenarios and their implications for urban energy and transport systems. Current opinion in environmental sustainability, 30, 89-102.

The IPCC Sixth Assessment Report on Climate Change Impacts. (2022). Population and Development Review, 48(2), 629–633. https://doi.org/10.1111/padr.12497

Yosef, G. B., Navon, A., Poliak, O., Etzion, N., Gal, N., Belikov, J., & Levron, Y. (2021). Frequency stability of the Israeli power grid with high penetration of renewable sources and energy storage systems. *Energy Reports*, *7*, 6148-6161.

Appendix 1: Input parameters

A1.1 Unit investment cost prediction of renewable energy and ESS technology

The projected unit cost of renewable energy and ESS are shown below. The prediction is conducted by Schmidt et al. (2019) and Huh et al. (2014).

Table.A 1. Unit cost of power

Power capacity(Thousand won/kW)					
Year	**Wind**	**Solar**	**Li**	**PHES**	**HSS**
2023	2548	2184	330.5928	1298.35	4560.031
2024	2533.459	2069.87	297.8454	1298.35	4335.767
2025	2519.689	1966.855	265.098	1298.35	4111.503
2026	2505.994	1868.967	247.9446	1298.35	3949.535
2027	2492.373	1775.951	230.7912	1298.35	3787.566
2028	2478.827	1687.564	213.6378	1298.35	3625.598
2029	2465.354	1603.576	196.4844	1298.35	3463.63
2030	2451.954	1523.767	179.331	1298.35	3301.662
2031	2438.628	1447.931	171.534	1298.35	3189.53
2032	2425.373	1375.869	163.737	1298.35	3077.398
2033	2412.191	1307.394	155.94	1298.35	2965.266
2034	2399.08	1242.327	148.143	1298.35	2853.134
2035	2386.041	1180.497	140.346	1311.334	2741.002
2036	2373.072	1121.745	137.2272	1311.334	2678.707
2037	2360.174	1065.917	134.1084	1311.334	2616.411
2038	2347.346	1012.868	130.9896	1311.334	2554.116
2039	2334.588	962.4587	127.8708	1311.334	2491.82
2040	2321.899	914.5582	124.752	1311.334	2429.525
2041	2309.279	869.0417	123.1926	1311.334	2392.147
2042	2296.728	825.7905	121.6332	1311.334	2354.77
2043	2284.245	784.6919	120.0738	1311.334	2317.393
2044	2271.83	745.6387	118.5144	1311.334	2280.015
2045	2259.482	708.5291	116.955	1324.317	2242.638
2046	2247.201	673.2664	115.3956	1324.317	2205.261
2047	2234.987	639.7587	113.8362	1324.317	2167.883
2048	2222.84	607.9187	112.2768	1324.317	2130.506
2049	2210.758	577.6633	110.7174	1324.317	2093.129
2050	2198.742	548.9136	109.158	1324.317	2055.752

Table.A 2. Unit cost of energy

Energy capacity(Thousand won/kWh)			
Year	Li	PHES	HSS
2023	391.0552	92	26.0958
2024	352.3186	92	24.8124
2025	313.582	92	23.529
2026	293.2914	92	22.6021
2027	273.0008	92	21.6752
2028	252.7102	92	20.7483
2029	232.4196	92	19.8214
2030	212.129	92	18.8945
2031	202.906	92	18.2528
2032	193.683	92	17.6111
2033	184.46	92	16.9694
2034	175.237	92	16.3277
2035	166.014	92.92	15.686
2036	162.3248	92.92	15.3295
2037	158.6356	92.92	14.973
2038	154.9464	92.92	14.6165
2039	151.2572	92.92	14.26
2040	147.568	92.92	13.9035
2041	145.7234	92.92	13.6896
2042	143.8788	92.92	13.4757
2043	142.0342	92.92	13.2618
2044	140.1896	92.92	13.0479
2045	138.345	93.84	12.834
2046	136.5004	93.84	12.6201
2047	134.6558	93.84	12.4062
2048	132.8112	93.84	12.1923
2049	130.9666	93.84	11.9784
2050	129.122	93.84	11.7645

A1.2 Other technical parameters of ESS

Those parameters below are also from Schmidt et al. (2019).

Table.A 3. Other parameters of ESS

ESS type	Efficiency(%)	Lifespan(year)	Discharge time(hour)	Fixed O&M cost(Thousand won/MW)	Variable O&M cost(Thousand won/MWh)
Li	0.927362	13	6	11500	3.45
PHES	0.883176	55	7.6	9200	1.15
HSS	0.632456	18	39	52900	0

Abstract (Korean)

재생에너지는 기후 위기로 인해 제기된 문제들에 대해 지속 가능한 해결책으로 제시되고 있다. 이에 따라 대한민국 정부도 재생에너지와 원자력을 전환부문 탄소중립 달성 수단으로 고려하고 있다. 그러나 재생에너지의 출력 변동성과 불확실성으로 인하여 높은 재생에너지 비중을 목표로 한다면, 에너지 저장 장치(Energy Storage System, ESS)의 보조가 필요하다. 에너지 저장 장치는 부하보다 높게 생산된 전력을 다른 형태의 에너지로 저장했다가 고부하 시간대에 다시 계통으로 방출하여 재생에너지 출력 변동으로 인한 불안정성을 완화하는 식으로 재생에너지와의 유기적인 상호작용이 존재한다. 하지만 지속적으로 구체적인 설비 계획이 세워지고 증설이 진행되는 재생에너지와 달리, 에너지 저장 장치에 관한 구체적인 계획은 늦춰지고 있는 상황이다. 이에 설비확장계획모형을 통해 재생에너지와 에너지 저장 장치의 설비 계획을 동시에 최적화 하는 과정의 필요성을 강조하고, 개별적으로 계획했을 때와의 비용, 탄소중립 달성에 필요한 설비량, 출력제한량 결과를 비교해 보았다. 또한, ESS는 재생에너지와 달리 아직 상용화가 미흡한 설비라는 점에서 그 비용의 변화 추이의 불확실성을 고려하여, 기술 발전 속도가 증가하거나, 감소할 때 결과가 어떻게 변화하는지도 확인하였다.

그 결과, 동시최적화를 통한 계획이 2050년까지 탄소중립을 달성하는 데 필요한 재생에너지 설비량을 감소시키며, 설비 확장과 운용에 필요한 총 비용도 절감하였다. 또한 재생에너지의 출력제한률이 크게 감소해 탄소중립 달성 시점의 재생에너지의 운영 효율도 개선됨을 확인하였다. 또한, ESS 기술 발전 속도의 증가는 일차적으로는 에너지 저장 장치의 설비량 증가를 일으키며, 나아가 재생에너지 설비량 감소를 유발하여 비용을 절감하는 선순환이 발생하는 것을 확인하였다. 또한 출력제한률도 개선하였다.

본 연구는 대한민국의 정책 입안자들에게 재생에너지와 ESS 설비 동시 계획의 필요성을 강조하며, 동시에 에너지 저장 장치의 설비 비용의 변화 추이가 달라질 때, 생기는 변화에 대해 이해할 수 있도록 돕는다. 또한, 선행연구들과 다르게, 재생에너지 발전의 변동성과 ESS의 충전 및 방전 결정을 보다 세밀하게 묘사하기 위하여 1시간으로 설비의 운용 관련 변수의 해상도를 높였다. 이에 따라 설비 증설에 대한 필요를 보다 정확히 반영한 결과를 도출하였다.

주요어 : 재생에너지, 에너지저장장치, 전력계통 최적화, 설비확장계획, 탄소중립
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