[*ASSESSMENT OF REGIONAL ENERGY STORAGE SYSTEM DEPLOYMENT IN RESPONSE TO ENERGY TRANSITIONS IN TAIWAN*]

[Yi-Ya Yang, Industrial Technology Research Institute, +886-3-5919052, yiyayang2030@gmail.com]
[Yun-Hsun Huang, National Cheng Kung University, +886-6-2757575#62825, abshung@hotmail.com]
[Jung Hua Wu, National Cheng Kung University, +886-6-2757575#62808, hwaa@mail.ncku.edu.tw]

Introduction

As the Taiwan government set the energy transition target as one of the most critical policies in Taiwan, assuring sufficient and stable energy became a highly valued topic. This paper aims to simulate and understand future status when renewable accounts more in the electricity generation portfolio. The energy transition is a pathway toward transforming the global energy sector from fossil-based to zero-carbon by the second half of this century. At its heart is the need to reduce energy-related CO2 emissions to limit climate change (IRENA, 2018).

Owing to the scarcity of indigenous energy resources, Taiwan relies on imports for 98% of its energy requirements, highly dependent on fossil fuels. Considering energy security issues and the Paris Agreement, the Taiwanese government has initiated planning for energy transitions. It aims to increase renewable energy to 20% of total power generation and achieve a nuclear-free homeland by 2025. The total capacity setting target of solar power will be 20GW in 2025, including 3GW roof-type and 17GW ground-type. Also, the long-term target of wind power capacity is 6.7GW, consisting of 1.2 GW inland wind power and 5.5GW offshore wind power.

Table 1 Taiwan's Renewable Energy Capacity and Generation Target

Type	The capacity factor of renewable energy (MW)			The power generation of renewable energy (TWh)		
	2015	2020	2025	2015	2020	2025
Solar power	1,768	6,500	20,000	17	81	256
Inland wind power	687	814	1,200	17	20	29
Offshore wind power	8	520	5,500	0.2	19	198
Geothermal energy	0	150	200	0	10	13
Biomass	727	768	813	35	56	59
Hydropower	2,089	2,100	2,150	54	64	66
Fuel cell	0	22.5	60	0	2	5
Total	5,276	10,875	27,423	124	252	546

However, a high proportion of variable renewable energy (VRE) sources are prone to fluctuate power generation as the weather changes, causing the risk of intermittent power supply. With that in mind, Energy Storage System (ESS) is an essential option for facilitating VRE integration. Therefore, it is crucial to assess regional ESS requirements during energy transitions in Taiwan.

This paper develops a short-term power dispatch model based on a linear programming framework to incorporate the highly resolved generation data. Our model differs from previous applications of linear programming to electricity supply planning. We explicitly address the generation technology portfolios and ESS selection from a regional renewable energy generating perspective in linear programming frameworks and extend the formulation to reflect regional ESS requirements. The model is utilized to simulate the daily power generation performance of multiple energies in 12 months and simulates the charging and discharging operation of ESS. In other words, our model can explicitly account for ESS specification and its detailed process in each region based on hourly temporal resolutions and economic and operation performances.

Therefore, this study focused on VRE power generating and ESS deployment. This paper addressed the following areas:

1. Construct a short-term power dispatch model based on a linear programming framework to incorporate the highly resolved generation data.

2. Simulation of the actual operation of future ESS and PSH, and the model calculates the extra costs of installing ESS.

This study focused on a compromise to the deployment of ESS construction regarding future electrical power supply and environmental issues on the island of Taiwan. Therefore, this research excluded the following areas:

1.The development of electrical power supply and demand outside the island of Taiwan is excluded.

2.The regional power supply information only considers the generation of VRE due to the limitation of the research period. We only discussed the energy storage demand of renewable energy in each region.

3.The stability of the electricity network in Taiwan and the operational problems related to the system are excluded.

4.On-line, real-time power scheduling and contingency procedures in the event of an emergency are also excluded.

5.The cost of power generation only includes the price of the power generation side, which means that the interest cost and the costs of power transmission and distribution operations are excluded. The model simulates the hourly process of all energies in Taiwan in 2025, including solar photovoltaic (20GW), offshore wind (5.5GW), and inland wind (1.2GW). The model minimizes the total cost of satisfying regional electricity demand in every hour of four seasons. The simulation results come in hourly data of the electricity generation by source. The data can use to analyze the trends in future power supply and energy-storing demands.

Model Description

The core research purpose is to simulate the supplying status (including the electricity supply curve, the demand curve, the average generation cost, and the ideal ESS deployment) when achieving the energy transition goal in 2025.

Most of the power planning models in Taiwan divided the simulation period into years, which has a shortage of showing the operation of ESSs. Thus, we designed the model in a more detailed way. We set the modified unit in an hour and 24 hours to represent a day in one month to reflect the different power supply of variable energy and power demand in each season. And because the model considers an energy storage mechanism, we then change the title of a planning model into a dispatch model.

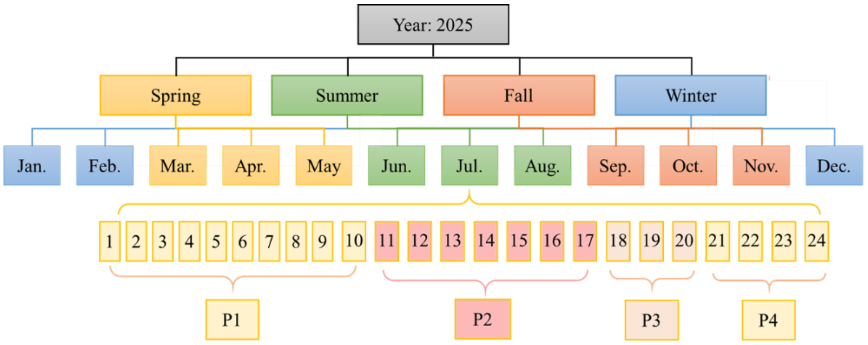

Figure 1 The time slice of the model.

Linear programming is a clear and intuitive method of mathematical programming. Its purpose is to assist decision-makers in planning the allocation of resources, that is, how to obtain the maximum utility at the lowest cost under the condition of limited resources. The basic form of linear programming can be expressed as follows:

Objective formula: $MIN\ Z = C_1X_1 + C_2X_2 + \ldots\ldots + C_nX_n$

Constraint functions: $S.T. f(x) \leq b$

Z represents the objective function. A linear programming model can solve both maximization problems and minimization problems. f(x) is the structured constraints: X is the vector of the decision variable; b is the right-hand-side (RHS) vector of the available resource.

The model constraints include satisfying electricity power demand, policies, the production constraints of the generator set, and the energy storage settings. The objectives and constraints in the model are described as follows:

1. Objective functions: Economy of power

The quality of Taiwan's power system is stable. If there is not much difference in power quality, the cost of power generation becomes a niche for power generation companies to compete with each other. The distribution of generator sets is mainly based on economic considerations (Yu-Hui Wang, 2011). The objective function can be express as (3-1):

$$\mathbf{min}\left(\sum_k \boldsymbol{TFC_k} + \sum_k \boldsymbol{TVC_k} \right) \qquad (3\text{-}1)$$

$$\boldsymbol{TFC_k} = \boldsymbol{n_k} \times \boldsymbol{fc_k} \qquad \boldsymbol{k} \in [\mathbf{1}, \mathbf{13}] \quad \boldsymbol{k} \in \mathbf{N} \qquad (3\text{-}2)$$

$$\boldsymbol{TVC_k} = \boldsymbol{EY_k} \times \boldsymbol{vc_k} \qquad \boldsymbol{k} \in [\mathbf{1}, \mathbf{13}] \quad \boldsymbol{k} \in \mathbf{N} \qquad (3\text{-}3)$$

$\boldsymbol{TFC_k}$: The total fixed costs of energy k. (Unit: $million)

$\boldsymbol{TVC_k}$: The total variable costs of energy k. (Unit: $million)

$\boldsymbol{n_k}$: The total installed capacity of energy k. (Unit: MW)

$\boldsymbol{fc_k}$**:** Average fixed cost of energy k. (Unit: $million/MW)

$\boldsymbol{EY_k}$: The total power generation in a year of energy k. (Unit: GWh)

$\boldsymbol{vc_k}$: Levelized unit variable cost of energy k. (Unit: $/kWh)

k: Represents each power generation energy. There are 13 energies in this study. The corresponding number and name of power energy are detailed in table 2.

Table 2 Technical number and total capacity (in 2025) chart.

k	Energy	*k*	Energy
1	Nuclear energy	*8*	Geothermal
2	Coal-fired	*9*	Solar power
3	Oil-fired	*10*	Offshore wind power
4	Gas-fired	*11*	Inland wind power
5	Biomass	*12*	Chemical ESS
6	Waste-to-energy	*13*	Pumped storage Hydro
7	Hydro		

2. Constraint: Satisfying electricity power demand

The purpose of power supply is to meet power demand. At present, the target value of the reasonable percent reserve margin approved by the government is 15%, so we converted the percent reserve margin to a limit of 15% more electricity generated per hour than required to achieve the rationality of power safety.

$$\sum_{k=1}^{8} EH_k + \sum_{k=9}^{11} ZH_k + \sum_{k=12}^{13} EH_k \geq DH \times (1 + sr) \quad \text{k} \in \text{N} \qquad (3\text{-}4)$$

EH_k: The amount of electricity generated by source k in an hour. (Unit: MW)
ZH_k: The amount of electricity enters the grid by source k in an hour. (Unit: MW)
DH: The predicted power demand in an hour. (Unit: MW)
sr: The percent operating reserve. In this study, percent operating reserve is set as 15%.

3. Constraint: Policies

"The proportion of renewable energy grows to 20% by 2025" has become the most critical policy goal in Taiwan's energy transition. In the latest government plan, the proportion of coal-fired power generation will drop to 27%, and the ratio of gas will exceed 50% in 2025. Equation 3-5~3-7 represents the shares of annual power generation of the above three energy sources.

$$\sum_{k=5}^{8} EY_k + \sum_{k=9}^{11} ZY_k + \sum_{k=12}^{13} EY_k \geq TY \times 20\% \qquad (3\text{-}5)$$
$$EY_2 \leq \mathrm{TY} \times 27\% \qquad (3\text{-}6)$$
$$EY_4 \geq TY \times 50\% \qquad (3\text{-}7)$$
$$\sum_{k=1}^{13} EY_k - \sum_{k=9}^{11} EY_k + \sum_{k=9}^{11} ZY_k = TY \qquad (3\text{-}8)$$

EY_k: The total amount of electricity generated by source k in a year. (Unit: GWh)
ZY_k: The total amount of electricity actually enters the grid by source k in a year. (Unit: GWh)
TY: Total power generation of all units (except the charged amount of VRE) that enter the grid. (Unit: GWh)

4. Constraint: The production constraints of the generator set

The electricity demand is not a constant; instead, when dramatic changes in the environment do not occur, electricity demand changes under a periodical circulation due to changes in climate conditions and electricity usage habits (Li Ko, 2014). Thus, the usability ratio was incorporated in this constraint model to reflect actual operating conditions.

$$EH_k \leq n_k \times eu_k \quad k \in [1,13] \;\; k, \in \mathrm{N} \qquad (3\text{-}9)$$
$$EH_k \geq n_k \times el_k \quad k \in [1,13] \;\; k \in \mathrm{N} \qquad (3\text{-}10)$$

eu_k: The high-end usability ratio of source y *k*, which represents of the maximum availability of *k* in each hour and region.
el_k: The low-end usability ratio of source *k*, which represents of the minimum availability of *k* in each hour and region.

5. Constraint: Energy storage settings

The ESS and PSH are no generator, but store existing electricity generated by VRE and releases them later. The following restrictions illustrate the storage settings of the ESS and PSH.

First, the model needs to distinguish the power generated by VRE between the energy entering the grid and the storing electricity. In eq. 3-11, factor *ZH* indicates the electricity entering the grid, which must be less than the actual electricity generated by the origin VRE sets in an hour.

$$ZH_k \leq EH_k \qquad k \in [9,11] \qquad k \in \mathrm{N} \qquad (3\text{-}11)$$

Second, referring to the government's planning, we restrict that ESS can only store solar power and inland wind power. In contrast, PSH only keeps offshore wind power in the middle region of Taiwan. Factor *CH* stands for the amount of electricity charged into the ESS and PSH within an hour.

$$ZH_9 + ZH_{11} + CH_{12} \leq EH_9 + EH_{11} \qquad (3\text{-}12)$$
$$ZH_{10} + CH_{13} \leq EH_{10} \qquad (3\text{-}13)$$

CH_k: The amount of power charged by ESS(*k=12)* or PSH (*k=13)* in an hour. (Unit: MW)

Third, the storage level *(h)* in any hour *h* equals the storage level in the previous hour *(h-1)*, plus the energy-charged, and minus the energy discharged from the system (eq. 3-14). To make sure the storage level does not exceed the storage capacity of its own, eq. 3-15 is applied.

$$S_k(h) = S_k(h-1) + CH_k(h) - EH_k(h) \qquad k \in [12,13] \;\; k \in N \qquad (3\text{-}14)$$
$$S_k(h) \leq Limit_k \qquad k \in [12,13] \;\; k \in N \qquad (3\text{-}15)$$

$S_k(h)$: The storage level of ESS and PSH. (Unit: MWh)
$Limit_k$: The storage capacity of ESS and PSH (Unit: MWh).
h: Represents each hour in 4 seasons. In this model, there are 24*4=96 hours.

Fourth, the charge amount and the discharge amount of power in the ESS and PSH need to be equal. Since chemical batteries cannot charge and discharge the same amount of electricity, a factor that represents the efficiency of storage technology of ESS. is the ratio of electricity spent to pumped divided to the electrical discharge, which is applied in eq.3-17 to represent the power lost for pumping water.

$$\sum_i ED_{12}(i) = \sum_i CD_{12}(i) \times \eta_{12} \qquad \mathrm{i} \in [1,12] \ \ i \in N \qquad (3\text{-}16)$$

$$ED_{13}(i) = CD_{13}(i) \times \eta_{13} \qquad \mathrm{i} \in [1,12] \ \ i \in N \qquad (3\text{-}17)$$

$ED_{12}(i)$: The power released from ESS in a day. (Unit: MWh)
$CD_{12}(i)$: The power charged from ESS in a day. (Unit: MWh)
η_{12}: The efficiency rate of ESS.
η_{13}: The efficiency rate of PSH.
i: Represent each month in a year.

Fifth, Without a substantial energy storage mechanism, the model will not choose to apply energy storage equipment to avoid additional expenditures, making the setting of the storing tool more critical. We referred to the papers of relevant research and sorted out solar and wind power storage mechanism, which is called Distribution Deferral (Chen, Chang, & Cho, 2019), aims to shift the time of VRE generation. In this setting, we delay the solar power to smooth the sharp decline when the duck curve of residual load happens and prevent the second peak of traditional energy supply. Solar energy can still supply energy for at least one hour after sunset, and the energy output before sunset should be equal to the production after sunset. During the evening, the sum of the direct output of solar energy and the production of the ESS must be equal to the total output after sunset to delay the energy output of PV in the evening.

Last but not least, for the charging and discharging are divided into different parameters, all model variables are positive.

The model is a multi-region optimization model based on a linear programming framework to incorporate the highly resolved generation data. The result is a cost-minimal combination of optimal hourly dispatch of various energies. From the model results, we can see the operation by sources and the support effect of ESS. The detailed data processing process will be discussed in the next paragraph.

Data processing

This paragraph will introduce how the data processed and utilized in the model, including the installed capacities, availability ratios, and the most critical one, the costs of energies.

Before we start to focus on the capacity data of 2025, renewable energy only accounts for 14% of the total equipment capacity, while solar power has only 4,149MW, and offshore wind has just set 128MW in 2019.

1. Installed Capacity of each energy

In the model, the capacity data of each energy is a weighted average calculated in each season. We refer to Taipower's new energy development plan to add new installation or retire power units, including the nuclear units officially decommissioned in May 2025.

2.Availability ratios

The usability ratios are incorporated in this model to reflect actual operating conditions and make each unit have a reasonable power output. To simulate the power generation efficiency of different VREs in various regions of Taiwan, we collected the power generation and installed capacity in multiple areas of Taiwan in the past three years and obtained the average capacity factor after dividing power generation to install capacity. For figure 3~ 6, we summarized the average of the past three years' capacity factors of each VREs in four seasons.

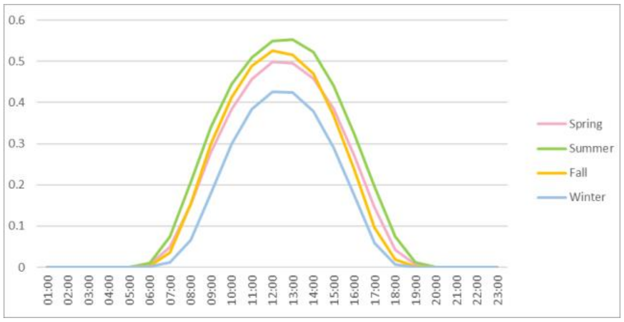

Figure 2 Average capacity factor of solar power in four seasons

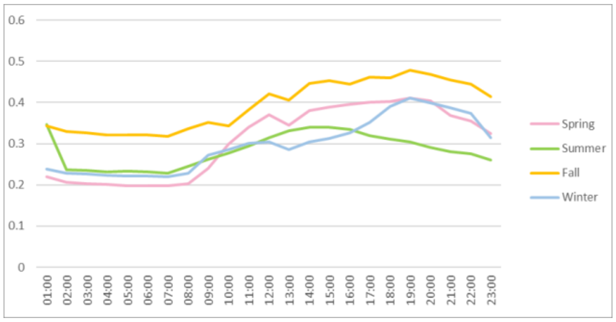

Figure 3 Average capacity factor of hydro power in four seasons

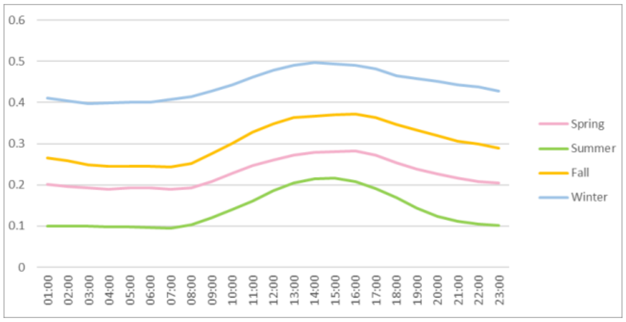

Figure 4 Average capacity factor of inland wind in four seasons.

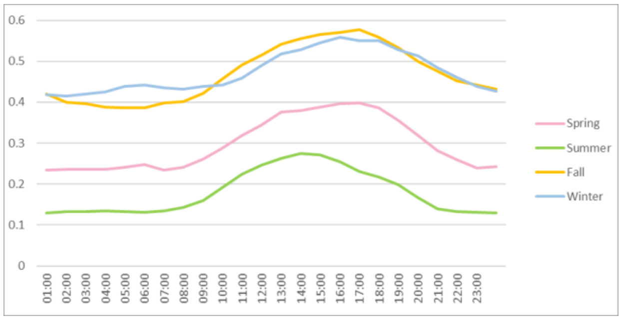

Figure 5 Average capacity factor of offshore wind in four seasons.

These capacity factors are then set as the upper limit of availability in VRE units, which are used to simulate the efficiency of renewable energy generation in different regions in different seasons.

For traditional power (nuclear, coal, oil, and LNG) availability settings, the restriction is based on the operating characteristics of the generator set to limit its power generation supply capacity. Since each parameter in the model represents the overall generation of each source, the use of the average capacity factor as availability ratio will risk overuse. Moreover, the proportion of renewable energy in 2025 is unprecedentedly high. In the future, a decline in the utilization rate of thermal power units can be expected. Thus, we use the unit function as the standard to set traditional power limits.

3.Costs of energies

Power generation cost has a remarkable influence on the model supply planning results. Generating costs of power units can be divided into fixed costs and variable costs. Fixed costs refer to the input of fixed capital such as generator sets, transmission and distribution circuits, and improved operation and maintenance in the power supply. The fixed costs only vary with the capacity of their generating units. Variable costs refer to each power unit's fuel, operation, and maintenance cost in the power supply, which varies with its annual power generation. The following will introduce the data processing process of this study in detail.

(1) Traditional Power costs:

The traditional power costs data used in the model was quoted from Hsin Lee's study (2019). Fixed costs of Taipower generator were converted from the information provided by Taipower Company, and the purchased energy from the private power plant was set to be 0 (only the variable costs of purchased energy are calculated). In the model, a single parameter represents the entire generator units by source, the fixed cost is calculated by the following formula:

$$\frac{\sum fixed\ cost\ of\ unit\ x \times install\ capacity\ of\ unit\ x}{total\ install\ capacity} = \text{Average fixed cost of energy k } (fc_k) \qquad \text{(Unit: \$million/MW)}$$

Variable costs are calculated originally from the annual power generation cost information provided by Taipower Company. Then we consider the future fuel cost increase rate, convert the fuel cost for each year. The fuel cost plus the operation and maintenance cost is the variable cost of the thermal power unit.

(2) VRE costs:

For the calculation of the fixed cost and variable costs of VRE, the calculation is based on the "Renewal Energy PV and wind power prices are based on the Feed-In Tariff (FIT) rates in Taiwan. The rate considers the capital cost at the beginning of the period, the capital reduction factor (the installation cost is evenly shared for 20 years), the annual operation and maintenance fee, and the annual electricity sales. We can then reverse the capital costs by looking into the FIT rates. According to the European Union Joint Research Centre (JRC, 2018), the average cost reductions of capital costs of inland wind, offshore wind, and solar photovoltaic from 2015 to 2020 were 0.56%, 3.13%, and 4.15%, respectively. From 2021 to 2030 the reductions were 0.38%, 0.43%, and 1.35%. Regarding the JRC's cost reduction forecast, we adjusted the fixed cost of newly added units in 2025. The Electricity Bulk Purchase Rate and the calculation of fixed cost is defined and calculated by the following formulas:

$$\frac{capital\ cost\ at\ the\ beginning\ of\ the\ period \times capital\ reduction\ factor + annual\ operation\ and\ maintenance\ fee}{Annual\ electricity\ sales}$$

$$= \text{ Electricity Bulk Purchase Rate}$$

$$\frac{\sum fixed\ cost\ of\ \ unit(old) \times install\ capacity\ of\ unit(old) + \sum fixed\ cost\ of\ \ unit(old) \times (1 - reduction\ rate) \times install\ capacity\ of\ \ unit(new)}{total\ installed\ capacity}$$

$$= \text{Average fixed cost of energy k } (fc_k) \qquad \text{(Unit: \$million/MW)}$$

(3) ESS cost:

Due to the diversified technologies of ESSs, the different discharge performances, and the differences in specifications significantly affect the cost, we use the Monte Carlo algorithm to deal with the randomness problem of cost interval. These homogenized cost data establish a small database of ESS.

The fixed cost of the ESS considers the initial construction capital and service life, regarding Taiwan's interest rate amortization for a fixed cost of 20 years. The variable cost includes the operation of the ESS and the local charging electricity price in Taiwan, which turns the foreign data into locally feasible variable cost in Taiwan.

Refer to Lazard (2018), "ESS designed to be paired with large solar PV facilities to improve the market price of solar generation, reduce solar curtailment and provide grid support when not supporting solar objectives" are classified as Utility-Scale ESS. The technologies assessed including Lithium-Ion, Flow Battery-Vanadium, and Flow Battery-Zinc Bromide. Considering the lithium-ion batteries are applied in existing demonstration ESSs in Taiwan, we used lithium-ion batteries as the ESS option in this study.

After considering the above data, the linear programming model will find the power generation portfolio with the lowest cost among different ESS configuration scenarios.

Empirical results

Before the simulation, we first set the 2019 scenario to check the reliability of the model. Through the validation, we are sure that the empirical results are reliable and worth trust.

The 2025 simulation results are presented in the hourly generation of various energies of four seasons in 2025. Taiwan’s last nuclear power unit retired in April 2025. Until then, it can provide 2% of daily electricity in winter and spring, accounting for 0.78% of annual electricity generation. After nuclear energy was decommissioned, the proportion of natural gas power generation increased, and the annual power generation increased to 52.20%. It is worth noting that natural gas power generation accounts for a relatively high output in the middle of the night, because solar photovoltaics cannot generate electricity in the night.

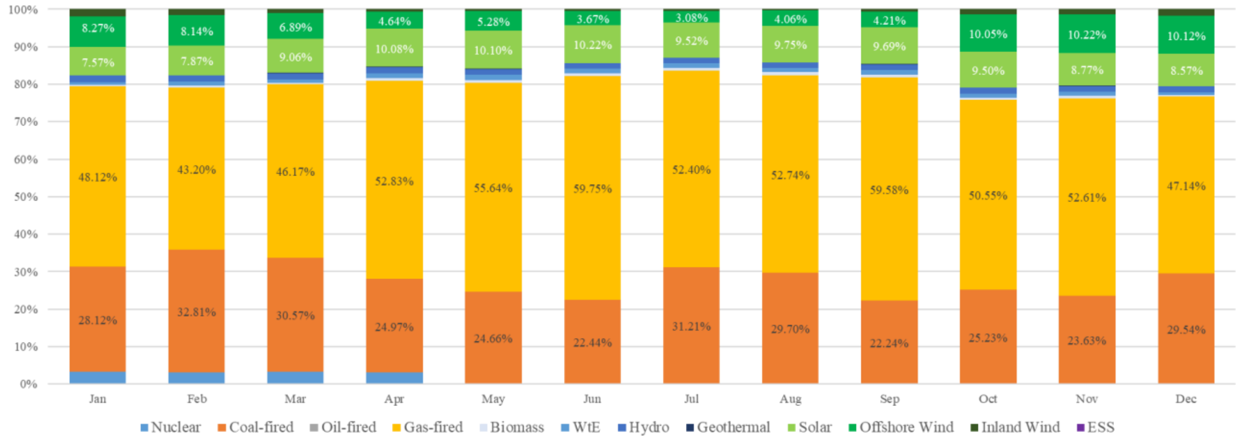

Figure 6 Total power generation in each month of 2025

Coal-fired generating units are still one of the main base loads in Taiwan. From the calculation results of the model, it is found that coal-fired units contribute the most in the spring, only 30% of the output in summer because there are abundant solar energy sources. In winter, the overall demand for electricity declines, coupled with the excellent performance of wind power in winter. Only 18.25% of the electricity needs to be provided. The reduction of coal-fired power may be expected to solve power generation pollution in winter.

During the peak hours of daylight, solar power can provide 20-29% electricity in a single hour, while wind power can provide 0.5%~2.5% at night. The results also indicate that the combination of Pumped-storage hydroelectricity (PSH) and chemical ESS can smooth out the sharp decline of PV electricity at sunset by storing excess solar energy at noon and release it in the evening. As a result, PSH and ESS can provide 2.6% ~3.1% of total electricity during the evening. The 600MW ESSs regulate an average of 0.26% of electricity in each season.

The southern region of Taiwan is rich in solar energy. Without energy storage, the power generation at noon (13:00) in summer is 10,656MW, and it will suddenly drop to less than 400MW by 18:00. In that time, the energy stored in the pumping water storage during the day can be released, paired with the ESSs, it can retard the effect of duck curve when the solar energy is greatly reduced.

The model recommended that each region of Taiwan, from north to south, can be installed with 8MW, 34MW and 578MW ESSs, which will be able to effectively integrate solar photovoltaic, and have good economic benefits. The blow chart shows the total electricity generation by sources in a representative day in August.

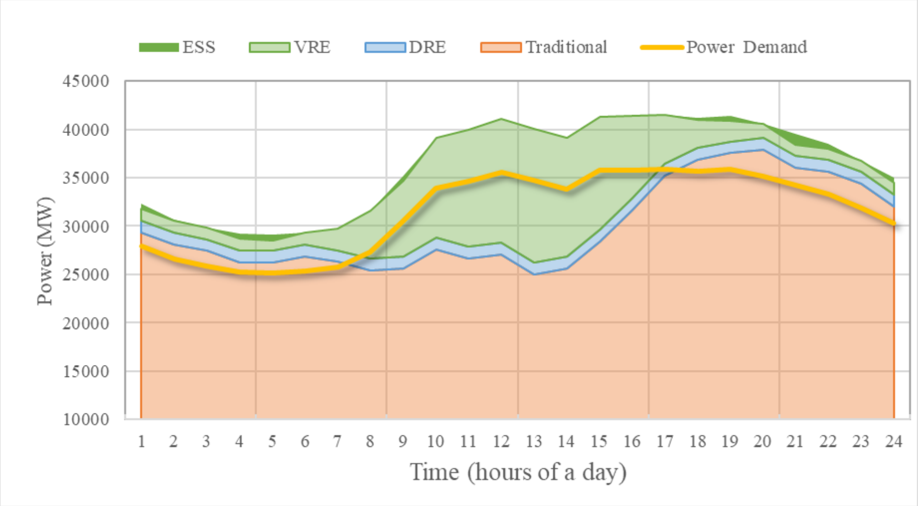

Figure 7 Power Supply Curve in a day of August (2025)

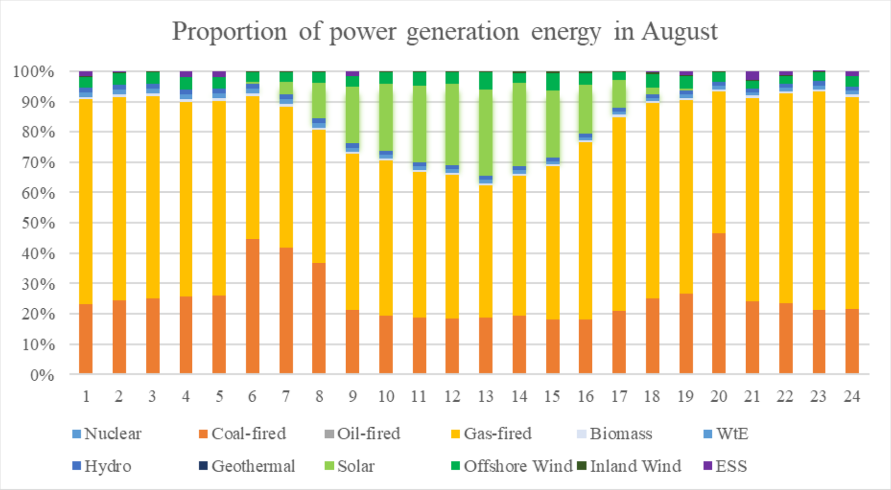

Figure 8 Proportion of power generation energy in a day of August

Conclusions

The simulation results show that according to the current policy planning, the target of 20% of renewable energy generation has a chance to be achieved, at the same time, coal-fired power generation will be reduced to 27%, and the nuclear power will be decommissioned in the end of 2025.

The application of the ESS works well when the solar energy rapidly reduces during sunset, which smooths the drastic fluctuations of variable renewable energy generated. Through considering regional characteristics of renewable energy, the contribution of this paper is to recommend the ESS deployment in each region, in order to meet the energy storage goal in Taiwan. The model recommended that each of the middle and southern region of Taiwan can be installed with 100MW and 500MW lithium-ion ESSs, which will be able to integrate solar photovoltaic, and have good economic benefits.

Since 2025, the location and target device capacity of all renewable energy sources have not been clear yet. In the future, through the update of government information, the parameters in the model can be refined.In 2025, the new peak time of traditional energy occurs in the night due to the absent of solar power. In the future, the back-up units (gas-fired units) should be stand by in the night times in case of the power shortage.

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