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Optimal Combination of Solar and Wind Power Generation and Energy Storage Systems to Realize Baseload Electricity Supplies with 100% Variable Renewable Energy

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Abstract

The development of a stable supply system for electricity with 100% renewable energy is needed by low-carbon societies working toward attaining the targets of the Paris Agreement. The purpose of this study was to evaluate the stable electricity supply systems in Japan supplied with 100% variable renewable energy (VRE) resources with a secondary battery system (SBS) or a hydrogen storage system (HSS) using a practical tool. For that purpose, the authors developed a practical tool based on a spread sheet to evaluate the stable electricity supply system without curtailment of VREs. Using the tool with actual time patterns of outputs of VREs in eastern Japan, the authors obtained the following results. The optimal capacity ratio of solar to wind is 3.3 with SBS and 4.4 with HSS. However, the system cost of stable electricity via SBS is over 100 JPY/kWh because of the high cost of batteries. The cost of a system with an HSS, at approximately 29 JPY/kWh, can be much lower than an SBS, because the energy storage cost of an HSS is much lower than that of an SBS.

Keywords: AMeDAS, output stability, variable renewable energy, secondary battery, hydrogen energy storage, 100% renewable system.

1. Introduction

The Japanese government intends to convert Japan into a low-carbon society to achieve the goals of the Paris Agreement in the 2050 scenario[1)]. In 2020, the Suga Cabinet's guidance statement set a higher goal of carbon neutrality in 2050[2)]. There are high expectations for variable renewable energy (VRE) resources such as solar and wind power generation as a means to decarbonize electricity systems. The Japanese government expects to utilize VRE resources as the baseload power supply, instead of conventional energy such as coal or nuclear power[2)]. However, energy supplies from VRE resources have cost and instability issues.

A baseload power supply is essential to maintain an independent, stable, and constant output of electricity. Because power demand varies with time of day and the seasons, the middle power supply and peak power supply ensure adequate electricity by continuously adjusting the output above baseload so as to meet changing power needs at any time. Many baseload power supplies by design are not flexible in output. However, wind power and solar power stabilized with energy storage may be capable of producing a constant baseload.

With a large amount of VRE grid interconnection, the "flexibility" of the power system becomes important, and grid-connected SBS and HSS play an important role. On the other hand, at the Energy Situation Roundtable of the Ministry of Economy, Trade, and Industry, as a decarbonized energy system, a "renewable energy/power storage system" that supplements the intermittent of VRE with a power storage system will be used. A trial calculation for realizing a baseload power supply or a peak power supply is shown[1)]. To make VRE the main power source, it is important to consider grid-connected SBS and HSS for adjusting grid-connected VRE and also a system that combines VRE with SBS and HSS to realize a stable power source.

In this study, we examined a stable electricity supply system with 100% VREs combined with SBS and HSS. Evaluation of the "flexible electricity supply system" with 100% VREs such as a peak load supply system is an issue for future work.

To meet the Japanese government's expectations, a better understanding of facilities and costs is required to assess the performance of VRE resources as a baseload power supply. If a constant output becomes possible, load tracking will become possible. An index for the future expansion of facilities was created by calculating costs using Japanese meteorological data. There is an optimum balance (Fig. 1) for minimizing costs when

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adding equipment to expand the solar and wind power generation system.

Energy storage, such as a secondary battery system (SBS) or a hydrogen storage system (HSS) is essential for developing a stable electricity supply system using 100% renewable energy.

Although an energy storage system is technologically feasible, the required storage capacity would be enormous. Additionally, the total storage capacity would proportionally affect the storage cost.

Previous research on renewable energy and storage includes performance evaluations of solar and wind power systems. The studies are roughly divided into those taking a macro perspective versus those taking a micro perspective.

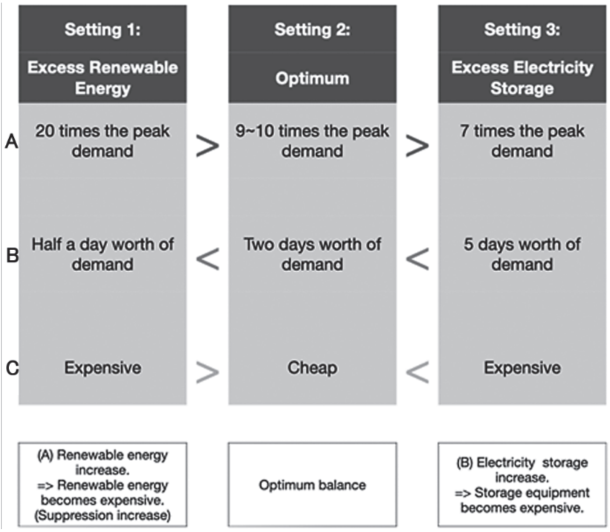


Fig. 1 An optimization of the VRE power and the storage capacity for stabilization required to find the best balance for total cost is minimization, where,
A: Renewable Energy kW,
B: Electricity Storage kWh,
C: Total cost; C = A x B.
The decision mechanism is based on renewable energy capacity and battery capacity. (The numbers are the example). This figure is a translation of the figure in p.46 of Ref 1) written in Japanese. However, the details of the trial calculation in Ref.1 have not been released.

Studies adopting a macro-scale approach evaluate an energy system model with several different energy resources, such as conventional energy, biomass, geothermal, solar, and wind power. For example, integrated modeling in Europe4) suggests optimization can be achieved through grid exchange and storage5), whereas the economic rationale of the VRE-based hydrogen production system in Japan6) suggests a cost advantage of HSS but does not consider the stable production of hydrogen. The scope of the studies described above extends to grid integration and are extremely valuable for understanding the energy system from a macro perspective. However, these studies do not evaluate system costs or the specific capacities and operations of the solar and wind power systems. Models that assessed the economic performance of HSS in Italy attempted to minimize costs by varying different coefficients and values. The Italian study dealt with solar and wind independently, but our assessment integrated these to seek additional cost reductions7).

Studies taking a micro-scale approach focus on combining solar and wind power. A useful simulation software code developed by Prasad and Natarajan8) optimized integrated solar and wind power generation systems with SBS and analyzed costs. However, the energy system in the model was assumed to be supplemented by electricity from the grid and did not include an HSS. An output simulation using data from California's electricity grid analyzed several combinations of solar and wind power generation systems and defined the efficiency when the best possible wind-solar groupings were achieved9). In our present study, the method for the optimization is similar but the total system costs were calculated with actual data.

Investigations for the development of a seasonal optimal combination of wind and solar power10) have shown the importance of analyzing reduced storage and balancing supply and demand11). These studies evaluated the optimal mix of VRE resources but did not consider the cost minimization. An earlier study12) estimated the required SBS capacity for stabilization of VRE systems in Japan; however, it did not consider the power storage loss. In our previous study13), the SBS capacity of the required energy storage was estimated for the stabilization of VRE systems in Japan. The combination of solar and wind power generation was found to drastically decrease the battery capacity needed for energy storage compared to individual power sources. This study did not estimate the cost and did not consider HSS for energy storage. The studies described above were all valuable for understanding the effectiveness of combining and optimizing solar and wind power generation systems. However, they did not evaluate the system cost. The study14) evaluated the stable supply of electricity and hydrogen and minimizing the supply costs considering the curtailment of VREs; however, the tool of the mathematical optimization is expensive and not practical for users of VREs.

The purpose of this study was to evaluate the stable electricity supply systems in Japan supplied with 100% variable renewable energy (VRE) resources with a secondary battery system (SBS) or a hydrogen storage system (HSS) using a practical tool. For that purpose, the authors developed a practical tool based on a spread sheet to evaluate the stable electricity supply system without curtailment of VREs.

2. Methodology

The tool the authors developed considered 100% VRE systems that maintain a stable output with solar power generation or wind power generation, and for energy storage that uses either SBS or HSS without curtailment of VREs. The output time patterns of VREs were based on actual solar and wind power generation data collected annually and hourly in eastern Japan, the electricity outputs of the systems were normalized at a constant output at 1 MW. Electricity is measured in hourly (h) time units; thus, the electrical energy generated by the power system for the unit of output (1 MW) in the unit of time (1h) is 1 MWh. The tool the authors developed is the practical tool on a spreadsheet of Microsoft Excel that is to be used by users of VREs.

Fig. 2 shows the assumed systems of this analysis. The tool used hourly solar and wind power generation data for one year to calculate the optimal facility capacity coefficient each for solar and wind power generation along with the costs of power generation and energy storage.

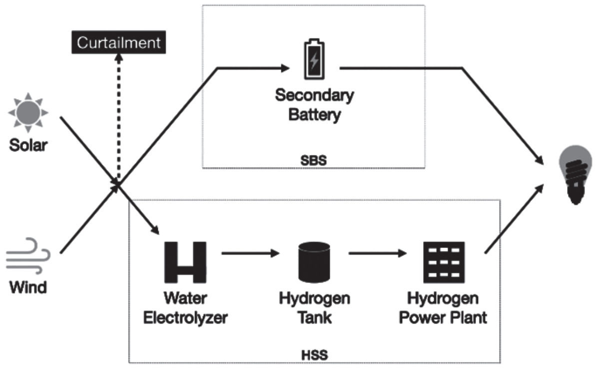


Fig. 2 Energy chain of SBS and HSS evaluated in the study*.
* : Curtailment is not included in this study.

2.1 Integration of Solar Power Generation and Wind Power Generation with Secondary Battery System

For this case, a 100% VRE system with an SBS was assumed for calculating the capacities, operation patterns, and total cost of the system in the following five steps, as illustrated in Fig. 3. For the readers convenience, the nomenclature of the parameters is shown in Appendix.

- Step 0: Set the starting value for the *FCC* (facility capacity coefficient) of VRE to 1.0.

- Step 1: Calculate *EE(t)* (Hourly electric energy) by multiplying *AEE(t)* (Actual hourly pattern of electric energy generation per MW of VRE resources) by *FCC*.

- Step 2: Define *BE(t)* (Surplus or shortage of outputs of VREs to maintain 1 MW output) as

$$EE(t) - 1.0 \text{ [MWh]}. \tag{1}$$

When *BE(t)* is greater than 0.0, *SEE(t)* (Stored electric energy) is equal to *BE(t)* multiplied by *EEC* (Energy efficiency coefficient based on energy loss during charge & discharge), that is, the energy stored in the battery, and *EEC* of SBS is 0.75[17]. When *BE(t)* is less than 0.0, *SEE(t)* is equal to *BE(t)*, that is, the amount of the discharged energy from the battery.

- Step 3: Calculate *ACE(t)* (Accumulative charged energy) using *SEE(t)*.

- Step 4: Determine *ESC* (Electric energy storage capacity) via

$$ESC = \max(ACE) - \min(ACE), \tag{2}$$

where the terms on the right side are the maximum and minimum values of *ACE* during a year.

- Step 5: Calculate *VREPGC* (VRE resources power generation cost), *SBC* (Secondary battery cost), and *TOC* (total cost) (Fig. 3).

In step 5, $VREPGUC_s$ (VRE resources power generation unit cost) is assumed to be 7,000 [JPY/MWh], $VREPGUC_w$ is assumed to be 8,500 [JPY/MWh], and *SBUC* (Secondary battery unit cost) is 2.0056 [million JPY/MWh] (as shown in subsection 2.2). *TOC* (Total cost) is the sum of *VREPGC* and *SBC*. $VREPGUC_k$ is VRE resources power generation unit cost, where

$$VREPGUC_s = 7 \text{ [JPY/kWh]} \tag{3}$$

$$VREPGUC_w = 8.5 \text{ [JPY/kWh]}, \tag{4}$$

according to the Japanese government target by 2030[20].

SBUC is secondary battery unit cost[17] where

$$\text{Equipment costs} = 23{,}000 \text{ [JPY/kWh]}, \tag{5}$$

(The cost of the inverter is totally included in the costs).

$$\begin{aligned}\text{Annual expense rate} &= \text{Interest rate} / (1 - (1+\text{Interest rate})^{-\text{Life}}) \\ &= 0.03 / (1 - (1+0.03)^{-20}) = 6.72\%,\end{aligned} \tag{6}$$

$$\begin{aligned}&\text{Operation and maintenance cost rate} \\ &= 2\% \text{ of the capital cost per year}\end{aligned} \tag{7}$$

and

$$\begin{aligned}SBUC &= \text{Equipment costs} * (\text{Annual expense rate} + \text{Operation and maintenance cost rate}) \\ &= 23{,}000 * (0.0672 + 0.02) \text{ [JPY/kWh]} \\ &= 2{,}005.6 \text{ [JPY/kWh]}.\end{aligned} \tag{8}$$

After the Step 5, a mathematical solver in Microsoft Excel is used, where the objective is *TOC* and the subject to is

$$ACE(0) = ACE(8760), \tag{9}$$

by adjusting the values of FCC_s and FCC_w. In the solver loop, the *TOC* is minimized by the Generalized Reduced Gradient method.

It was assumed

$$ACE(0) = ACE(8760) = 0.0 \qquad (10)$$

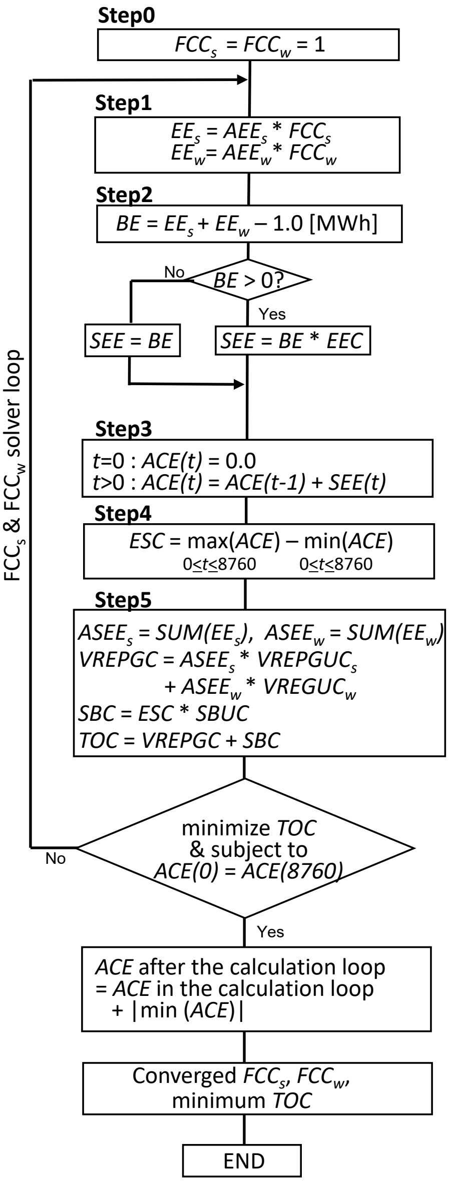
in the calculation loop. To avoid negative values for *ACE* during a year, *ACE* after the calculation loop was adjusted by *ACE* in the calculation loop plus the absolute value of min (*ACE(t)*).

Lithium iron phosphate secondary batteries[18] have a life of 15 years or more, the cycle life of 15,000 times or more, and a low self-discharge rate (several% / year). Therefore, this report assumes that the secondary battery will continue to advance in technology, and the self-discharge of SBS in 2030, which is the calculation target year, is ignored. Lifetime is assumed to be 20 years.

2.2 Integration of Solar Power Generation and Wind Power Generation with Hydrogen Storage System

For this case, a 100% VRE system with an HSS was assumed. The method for integrating solar and wind power generation systems is as follows, as illustrated in Fig. 4.

The methodology here is the same as in Steps 1–5 of subsection 2.1, except for the following differences:
In Step 2, *EEC* of HSS is 0.45[19]. The value of 0.45 is calculated by the water electrolysis efficiency at 80% multiplied by power generation efficiency at 56%.



FCC_k: facility capacity coefficient of variable renewable energy
k=s: solar power
k=w: wind power

EE_k: hourly electric energy [MWh]
AEE_k: actual hourly pattern of electric energy generation per MW of variable renewable energy resources [MWh]

BE: Surplus or shortage of outputs of VREs to maintain 1 MW output for 1 h [MWh]

SEE: stored electric energy [MWh]
EEC: energy efficiency coefficient based on energy loss during charge & discharge

ACE: accumulative charged energy [MWh]

ESC: electric energy storage capacity [MWh]

$ASEE_k$: annual sum of electric energy [MWh]
VREPGC: variable renewable energy resources power generation cost [JPY]
$VREPGUC_k$: variable renewable energy resources power generation unit cost [JPY/MWh]
SBUC: secondary battery unit cost [JPY/kWh]
TOC: total cost [JPY]

In Step 5, the *TOC* consists of *VREPGC*, *WEFC* (Water electrolysis facility cost), *HTC* (Hydrogen tank cost), and *HPPC* (Hydrogen power plant cost).

The unit costs of the facilities are as follows:

HTUC (hydrogen tank unit cost)[19]

$$HTUC = \text{Equipment costs} * (\text{Annual expense rate} + \text{Operation and maintenance cost rate}) / PCAL, \qquad (11)$$

where

$$\text{Equipment costs} = 5{,}000\ [\text{JPY/Nm}^3], \qquad (12)$$

$$\text{Annual expense rate} = \text{Interest rate} / (1 - (1 + \text{Interest rate})^{-\text{Life}}) = 0.03 / (1 - (1 + 0.03)^{-20}) = 6.72\%, \qquad (13)$$

the Operation and maintenance cost rate is 2% of the capital cost per year, *PCAL* is Power calculation from 1 Nm^3 hydrogen to kWh;

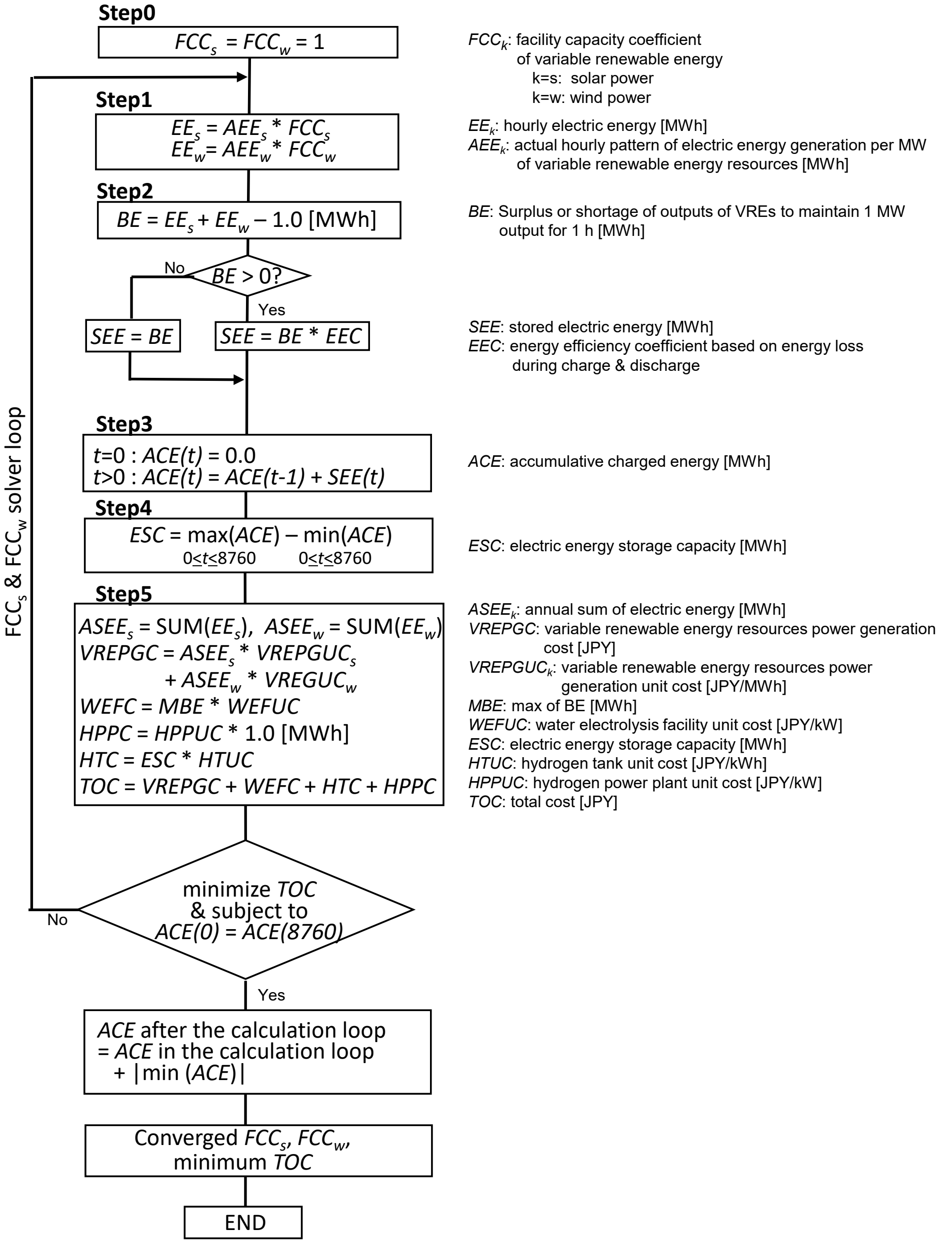
$$PCAL = 12.8\ [\text{MJ}] * (\text{Power generation efficiency of HSS}) / (3600\ [\text{second}] * 1000\ [\text{kWh/Nm}^3\ \text{hydrogen}]), \qquad (14)$$

and then

$$HTUC = 219.1\ [\text{JPY/kWh}]. \qquad (15)$$

HPPUC: hydrogen power plant unit cost[19]

$$HPPUC = \text{Equipment costs} * (\text{Annual expense rate} + \text{Operation and maintenance cost rate}) = 120{,}000 * (0.0672 + 0.02)\ [\text{JPY/kW}], \qquad (16)$$



FCC_k: facility capacity coefficient of variable renewable energy
k=s: solar power
k=w: wind power

EE_k: hourly electric energy [MWh]
AEE_k: actual hourly pattern of electric energy generation per MW of variable renewable energy resources [MWh]

BE: Surplus or shortage of outputs of VREs to maintain 1 MW output for 1 h [MWh]

SEE: stored electric energy [MWh]
EEC: energy efficiency coefficient based on energy loss during charge & discharge

ACE: accumulative charged energy [MWh]

ESC: electric energy storage capacity [MWh]

$ASEE_k$: annual sum of electric energy [MWh]
VREPGC: variable renewable energy resources power generation cost [JPY]
$VREPGUC_k$: variable renewable energy resources power generation unit cost [JPY/MWh]
MBE: max of BE [MWh]
WEFUC: water electrolysis facility unit cost [JPY/kW]
ESC: electric energy storage capacity [MWh]
HTUC: hydrogen tank unit cost [JPY/kWh]
HPPUC: hydrogen power plant unit cost [JPY/kW]
TOC: total cost [JPY]

Fig. 4 Optimization procedure for a combined solar and wind power system with a hydrogen storage system.

where

Equipment costs = 120,000 [JPY/kW], (17)

Annual expense rate

$= \text{Interest rate} / (1 - (1 + \text{Interest rate})^{-\text{Life}})$

$= 0.03 / (1 - (1 + 0.03)^{-20}) = 6.72\%$, (18)

Operation and maintenance cost rate is 2% of the capital cost per year, and then,

HPPUC = 10,464 [JPY/kW]. (19)

WEFUC: water electrolysis facility unit cost[19)]

WEFUC = Input power * Annual expense rate, (20)

where

Input power is 70,000 [JPY/kW-input][19)],

Annual expense rate is 15.88%[19)], and then,

WEFUC = 11,116 [JPY/kW] [19)]. (21)

According to the Hydrogen and Fuel Cell Strategy Roadmap (H31)[21)], FCV hydrogen storage cost is per 5kg hydrogen,300,000 yen or less (about 5400 yen / Nm^3 or less) in 2025, and 100,000 to 200,000 yen in 2030 (about 1800 to 3600 yen / Nm^3). It is explained that the target value for 2025 is set to make a FCV at the same price as a hybrid vehicle. However, for 2030, it only shows the target value without explanation of the numerical value. As for the stationary hydrogen storage cost, an estimated value cannot be obtained. Thus, the target value in 2025 was assumed to be 5000 yen / Nm^3 with reference to the stationary storage cost of hydrogen.

3. Application to Japanese VRE Systems

In this section, the calculation results are shown for the methodology described in section 2 applied to actual VRE resources power generation data[15)] from eastern Japan.

The VRE resources power generation data used[15)] consisted of VRE resources output time patterns created using sunshine and wind speed data collected by AMeDAS[16)] for one year (from 01/01/2010 to 12/31/2010) in eastern Japan (Hokkaido, Tohoku, and Kanto areas).

Partial examples (for 7 days) of the VRE resources power generation data collected by AMeDAS are shown in Fig. 5 (for solar power) and Fig. 6 (for wind power). It should be noted that the one-year data were used in this study.

Figure 7 shows the time variations of the calculation results in a week (1st Jan – 7th Jan), including BE, AEE$_S$ + AEE$_W$, SEE, ACE and the stable output (1 MWh energy for each hour, i.e., 1MW in average power each hour). The left axis corresponds to ACE, and the right axis corresponds to others.

3.1 Optimized Combination of Solar and Wind Power for Stabilization with the Secondary Battery System

The results obtained from applying the methodology in subsection 3.1 to the solar and wind power generation data are shown in Table 1. When combining solar and wind power using SBS as energy storage, the optimized ratio obtained is $FCC_s : FCC_w = 3.27 : 1.0$. The annual transition in the *ACE* using the optimized ratio is shown in Fig. 8.

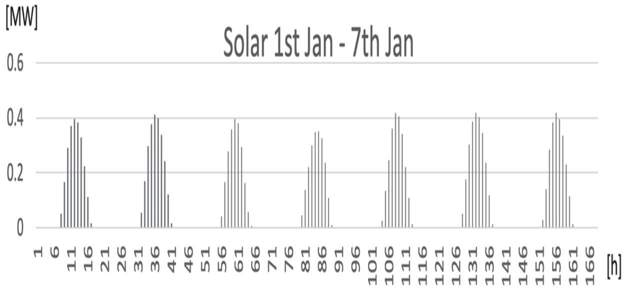


Fig. 5 Sample data for one week of actual electric power generation every hour by solar power, based on AMeDAS[16)] data in 2010.

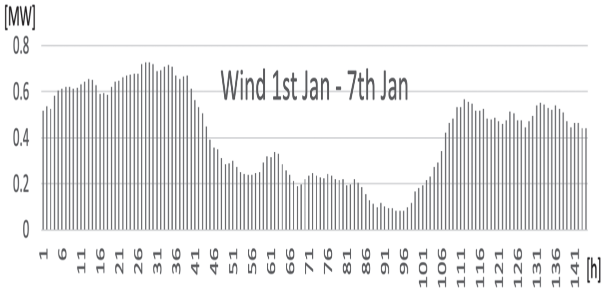


Fig. 6 Sample data for one week of actual electric power generation every hour by wind power, based on AMeDAS[16)] data in 2010.

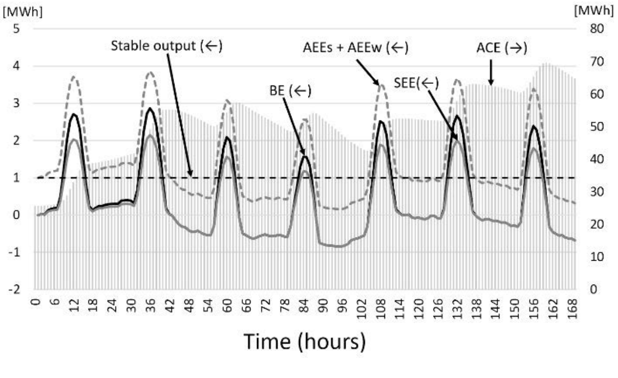


Fig.7 Time variations of calculated parameters for a week (0:00 on 1st Jan to 23:59 on 7th Jan).

3.2 Optimized Combination of Solar and Wind Power for Stabilization with the Hydrogen Storage System

An optimization similar to that in subsection 3.1 is also possible in the case of HSS. The results obtained by applying the methodology in subsection 2.2 to the solar and wind power

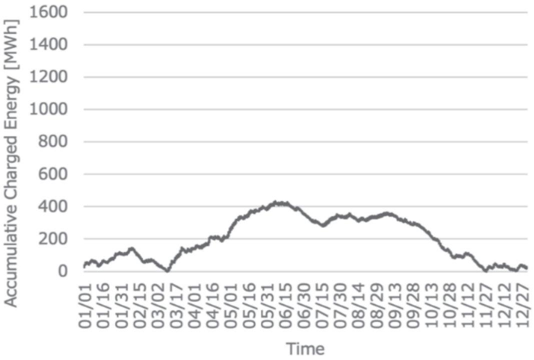


Fig. 8 Annual transition in the accumulative charged energy (*ACE*) for the secondary battery system of an optimized combination of wind and solar power, using the optimized ratio $FCC_s : FCC_w = 3.27 : 1.0$[13].

Table 1 Summary of results for the case of the secondary battery system with an optimized combination of solar and wind power.

Annual Sum of Electric Energy from Solar Power Generation ($ASEE_s$) [MWh]	6,401
Annual Sum of Electric Energy from Wind Power Generation ($ASEE_w$) [MWh]	3,500
Energy Storage Capacity (*ESC*) [MWh]	432 [13]
ESC / MW * (day / 24 h) [days]	18.0 [13]
Facility Capacity Coefficient (*FCC*) of Solar Power Generation	6.27 [13]
Facility Capacity Coefficient (*FCC*) of Wind Power Generation	1.92 [13]
VRE resources Power Generation Cost (*VREPGC*) [million JPY]	75
Secondary Battery Cost (*SBC*) [million JPY]	866
Total Cost (*TOC*) [JPY/kWh]	107.3

generation data are shown in Table 2. When combining solar and wind power using HSS as energy storage, the optimized ratio obtained is $FCC_s : FCC_w = 4.39 : 1.0$. The annual transition in the *ACE* using the optimized ratio is shown in Fig. 9.

3.3 Comparison of the Secondary Battery System and Hydrogen Storage System

Our analysis shows that an enormous energy storage capacity will be essential for stabilizing of the output power of solar and/or wind power systems. The SBS cost increases linearly with the greater required capacity. On the other hand, the HSS cost consists of two parts: the water electrolysis facilities and the hydrogen storage tank.

The hydrogen tank cost for unit energy (MWh) is usually much lower than the secondary battery cost. In this study, the following values were used based on references[17, 19], as shown in section 2;

Hydrogen tank unit cost, *HTUC* is 219.1 [JPY/kWh],

Secondary battery unit cost, *SBUC* is 2,005.6 [JPY/kWh].

Therefore, the total cost for storage with an HSS can be expected to be lower than storage with an SBS in the case of full stabilization over a long period, i.e., for one year, as shown in this study.

Our cost analysis results are summarized in Fig. 10. In the three patterns, the energy storage costs for the HSS (hydrogen power plant cost plus water electrolysis facilities cost) are only 14% to 27% of costs for the SBS.

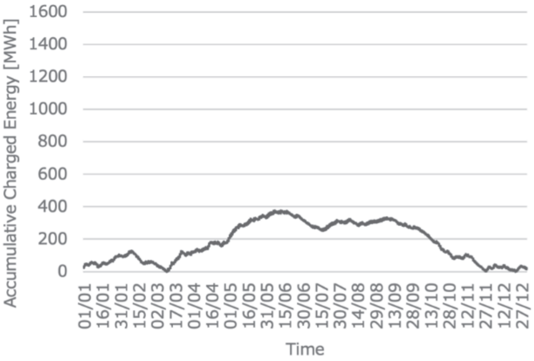


Fig. 9 Annual transition in the accumulative charged energy (*ACE*) for the hydrogen storage system of an optimized combination of wind and solar power, using the optimized ratio $FCC_s : FCC_w = 4.39 : 1.0$.

For both storage types (SBS and HSS), significant cost reductions are obtained through solar and wind combinations.

SBS is advantageous for conversion efficiency, and HSS is advantageous for the storage cost per unit-energy. When comparing the two types of energy storage systems, the energy storage costs of the HSS (hydrogen power plant plus storage tank plus water electrolysis facilities) were found to be more economical in terms of the total cost to provide constant electricity output. The system cost of stable electricity via SBS is over 100 JPY/kWh because of the high cost of batteries, and via HSS is 29 JPY/kWh at approximately. Therefore the HSS cost is only 14% to 27% of the SBS cost.

As a result of cost calculation using the estimated unit costs for 2030, the cost superiority of the HSS is significant (the cost difference is more than 200%) (Fig. 10). Thus, even if there was some error in the future unit cost estimate, it appears that the cost superiority of HSS over SBS would be robust.

The analyses for this study were based on data from a specific year (in 2010). The model's accuracy is expected to improve as it is applied to other years in future studies.

Table 2 Summary of results for the case of the hydrogen storage system with an optimized combination of solar and wind power

Annual Sum of Electric Energy from Solar Power Generation ($ASEE_s$) [MWh]	9,057
Annual Sum of Electric Energy from Wind Power Generation ($ASEE_w$) [MWh]	3,686
Energy Storage Capacity (*ESC*) [MWh]	378
ESC / MW * (day / 24 h) [days]	15.7
Facility Capacity Coefficient (*FCC*) of Solar Power Generation	8.87
Facility Capacity Coefficient (*FCC*) of Wind Power Generation	2.02
VRE resources Power Generation Cost (*VREPGC*) [million JPY]	95
Hydrogen Tank Cost (*HTC*) [million JPY]	83
Hydrogen Power Plant Cost (*HPPC*) [million JPY]	10
Water Electrolysis Facilities Cost (*WEFC*) [million JPY]	65
Total Cost (*TOC*) [JPY/kWh]	28.8

4. Conclusions

The purpose of this study was to evaluate the stable electricity supply systems in Japan supplied with 100% variable renewable energy (VRE) resources with a secondary battery system (SBS) or a hydrogen storage system (HSS) using a practical tool. For that purpose, the authors developed a practical tool based on a spreadsheet to evaluate the stable electricity supply system without curtailment of VREs. Using the tool with actual time patterns of outputs of VREs in eastern Japan, the authors obtained the following results. Two energy storage methods, the SBS and HSS, were compared. When the solar power and wind power systems were integrated at optimal ratios, the required storage capacities were reduced to approximately 18 days with SBS and 16 days with HSS. Compared to solar or wind power generation systems alone, both combined resulted in a substantial decrease in the required energy storage capacity from 32% to 45% in the SBS case and 60% in the HSS case. The optimal ratio of solar to wind is 3.3 with SBS and 4.4 with HSS. The system cost of stable electricity via SBS is over 100 JPY/kWh because of the high cost of batteries, and via HSS is 29 JPY/kWh at approximately. The HSS cost is only 14% to 27% of the SBS cost.

The curtailment of VRE resources (i.e., stopping the output) is not evaluated in the practical tool based on a spreadsheet. It is the future task to consider curtailment on the practical tool on a spreadsheet that is to be available for users of VREs.

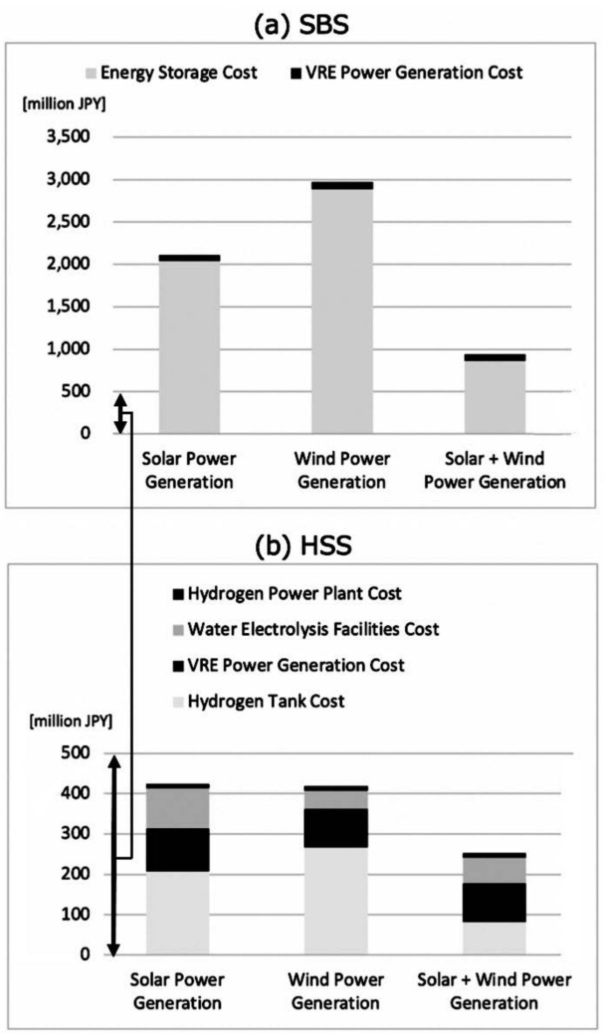


Fig. 10 Annual costs to stabilize the 1 MW output power of VRE systems: (a) SBS[12] and (b) HSS. This study shows that the annual cost range for HSS will be only 14% to 27% of that for the SBS.

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Appendix: Nomenclature of Parameters

"k" represents variable renewable energy resources type,
where $k = \{s, w\}$, s: solar power, w: wind power
"t" indicates the time in hours, where t = {0~8760}.

ACE(t): accumulative charged energy [MWh]
$AEE_k(t)$: actual hourly pattern of electric energy generation per MW of variable renewable energy resources [MWh]
$ASEE_k$: annual sum of electric energy [MWh]
BE(t): Surplus or shortage of outputs of variable renewable energies to maintain 1 MW output for 1 h [MWh]
$EE_k(t)$: hourly electric energy [MWh]
EEC: energy efficiency coefficient based on energy loss during charge & discharge
ESC: electric energy storage capacity [MWh]
FCC_k: facility capacity coefficient of variable renewable energy
HPPC: hydrogen power plant cost [JPY]
HPPUC: hydrogen power plant unit cost [JPY/kW]
HTC: hydrogen tank cost [JPY]
HTUC: hydrogen tank unit cost [JPY/kWh]
MBE: max of *BE* [MWh]
SBC: secondary battery cost [JPY]
SBUC: secondary battery unit cost [JPY/kWh]
SEE(t): stored electric energy [MWh]
TOC: total cost [JPY]
VREPGC: variable renewable energy resources power generation cost [JPY]
$VREPGUC_k$: variable renewable energy resources power generation unit cost [JPY/MWh]
WEFC: water electrolysis facility cost [JPY/MW]
WEFUC: water electrolysis facility unit cost [JPY/kW]