Bid Determination Method for an Electricity Market with State-of-Charge Maintenance of a Compressed Air Energy Storage System Using the Prediction Interval of Wind Power Output

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***Abstract*—The use of power from wind power plants (WPPs) has increased in recent years, and the power from WPPs can be traded in electricity markets. Operators of WPPs need to determine bid volume before the power is supplied to the electricity market. The bid volume can be determined based on the power forecast data; however, uncertainty in the power can lead to imbalance between the bid volume and the actual output from WPPs. Using an energy storage system (ESS) is an effective solution, but the state-of-charge (SOC) should be maintained at an appropriate value to effectively use the ESS. Bids often include the energy required for SOC maintenance. However, imbalance can occur if the energy equals the ESS rated power under uncertainty because the ESS cannot use more power than the rated power. Therefore, the control of the energy required for SOC maintenance should be discussed. In this paper, we propose a bid determination method using a prediction interval to reduce imbalance by controlling the energy required for SOC maintenance. Wind farms with a compressed air energy storage system are considered, and numerical simulations are performed. As a result, our proposed method with the prediction interval can reduce the degree of imbalance in comparison with methods without the prediction interval.**

Keywords—bid determination, electricity market, energy storage system, prediction interval, wind power

NOMENCLATURE

$t = \{1, 2, \dots 48\}$	Index sets of time every 30 min.
$t_s = \{1, 2, \dots 180\}$	Index sets of time every 10 sec.
$I = \{1, 2, \dots 47\}$	Interval sets of 30 min.
P_I^{FC}	Forecasted power at interval *I* [kw].
P_I^{FC-}	The 2.5th percentile forecasts at interval *I* [kw].
P_I^{FC+}	The 97.5th percentile forecasts at interval *I* [kw].
$P_{t_s,I}^{AO}$	Actual output of wind power plants at time t_s and interval *I* [kw].
$\Delta P_{t_s,I}^{FE}$	Forecast errors at time t_s and at interval *I* [kw].
$\Delta P_I^{PI+}, \Delta P_I^{PI-}$	Prediction interval at interval *I* [kw].
CP_{rated}	Rated capacity of the ESS [kwh]
P_{rated}	Rated power of the ESS [kw].
$P_I^{UP_c}$	Upper limit of required power for SOC maintenance when the ESS requires to charge at interval *I* [kw].
$P_I^{UP_d}$	Upper limit of required power for SOC maintenance when the ESS requires to discharge at interval *I* [kw].
P_I^{RQ}	Required power for SOC maintenance at interval *I* [kw].
E_I^{RQ}	Required energy for SOC maintenance at interval *I* [kwh].
E_t^{BID}	Bid volume at time *t* [kwh].
SOC_t	State of charge (SOC) of the ESS at time *t*.
SOC_t^{EST}	Estimated SOC at time *t*.
SOC_{TRG}	Target SOC.

New Energy and Industrial Technology Development Organization (NEDO)

I. INTRODUCTION

Wind power generation does not emit carbon dioxide, and it is effective in the prevention of global warming. However, power from wind power plants (WPPs) tends to fluctuate because of change in wind speed/direction. Therefore, power from WPPs is not steady, and it cannot be handled easily. In various countries, the renewable portfolio standard and/or the feed-in tariff (FIT) have been introduced to promote the use of renewable energies, including wind power [1]. Currently, power from WPPs is sold at a fixed price in the FIT in Japan; however, the policy may change. After the FIT ends, power from WPPs will be traded in the electricity market. As a result, operators of WPPs need to determine the bid volume before the power is supplied to the electricity market [2]; the bid volume is defined as the amount of electricity that is up for bids. The bid volume can be determined using the power forecast data. Nonetheless, the uncertainty in the use of power can lead to imbalance between the bid volume and the actual output from WPPs.

One of the effective solutions to reduce this imbalance is using an energy storage system (ESS) that uses a charging and discharging protocol. In [3], a planning and operating method using the ESS was proposed, and the economic feasibility was evaluated. In [4], forecast errors were considered and rolling optimization models were developed for bidding and real-time control using the ESS. In [5], the partition of the ESS power and energy capacity were considered, and a dispatch scheduling method was proposed using ESS. However, electricity cannot be discharged or charged if ESS is empty or full Thus, a state-of-charge (SOC) of an ESS should be maintained at an appropriate value. In previous work, we proposed methods to maintain the SOC while bidding, and indicated that the maintenance of the SOC is effective in reducing the imbalance [6]–[8]. Forecasted energy is divided into energy for bids and energy for SOC maintenance; the energy required to maintain the SOC can be the same as the ESS rated power when the SOC is far from the target value. However, imbalance can occur if the required energy is equal to the ESS rated power under uncertainty because the ESS cannot use more power than the rated power. Therefore, control of the required energy for SOC maintenance should be discussed.

Considering the prediction interval can be effective in solving this problem. The prediction interval of forecast data expand the range of the forecast and increase the probability that the forecast coincides with actual output. However, further study about the determination of bids using the prediction interval to maintain the SOC is required.

In this paper, we propose the determination method of bids using the prediction interval of forecast data from Japan to maintain the SOC of the ESS. In particular, we focus on the intraday market: Gate Closure (GC) is 1 h before the beginning of time-of-delivery (ToD). The SOC at the beginning of ToD is estimated, and bids are determined with the SOC maintenance, based on the prediction interval of the forecast data. Wind farms in the Tohoku region of Japan and a compressed air energy storage (CAES) are considered, and a numerical simulation is performed. The results including the SOC frequency, total bid volume, and degree of imbalance are evaluated to understand the optimality of the proposed method. As a result, this study can contribute to further practical determination of bids and the efficient use of ESS.

The authors participated in a project commissioned by New Energy and Industrial Technology Development Organization (NEDO) and studied the CAES system in Higashi-izu, Japan. An experiment using the CAES was conducted and analyzed [9].

The rest of this paper is organized as follows. Section 2 introduces a framework of the Japanese electricity market, the prediction interval of forecast, and the bid determination method. Section 3 explains the simulation conditions. Section 4 provides and evaluates the simulation results. Further results are presented and discussed in Section 5, and Section 6 concludes this paper.

II. Methodology

A. Japanese Market Framework

Japanese electricity market consists of the spot market and the intraday market. In those markets, the WPP operators should decide the bid volume and make the bids. The spot market is the main market and the electricity supplied the next day is traded in this market. The GC of the spot market is 10:00 AM. The intraday market is opened to adjust electricity after the bid in the spot market [2]. This paper focuses on the intraday market in Japan. The GC of the intraday market is 1 h before the ToD that is set every 30 min. For example, it is set at 0:00, 0:30, and 1:00. Each product is the amount of energy with a time unit of 30 min; therefore, 48 products can be traded in a day. The operators should generate and supply the same amount of energy as the bid volume. If the supplied energy does not match the bid volume, the difference between them is penalized as imbalance. Although the intraday market closes 1 h before the ToD, the bid volume is started to decide 1.5 h before the ToD to spare 30 min for the determination and to meet the deadline in this study. In this paper, the situation that all the bids are accepted is assumed. The framework of the intraday market is depicted in Figure 1.

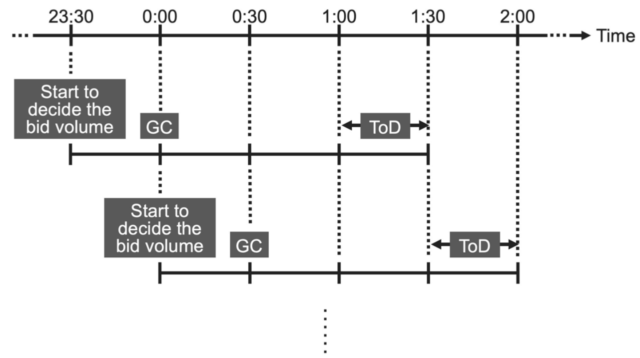


Fig. 1. Framework of the intraday market in Japan. GC of the intraday market is 1 h before the ToD that is set every 30 min. Each product is the amount of energy in 30 min, and 48 products are traded in a day. For example, GC is at 0:00 when the ToD is 1:00–1:30, and GC is at 0:30 when the ToD is 1:30–2:00, as shown in the figure. The operators should generate and supply the same amount of energy as the bid volume. The bid volume is started to decide 1.5 h before the ToD to spare 30 min for the determination and to meet the deadline in this study.

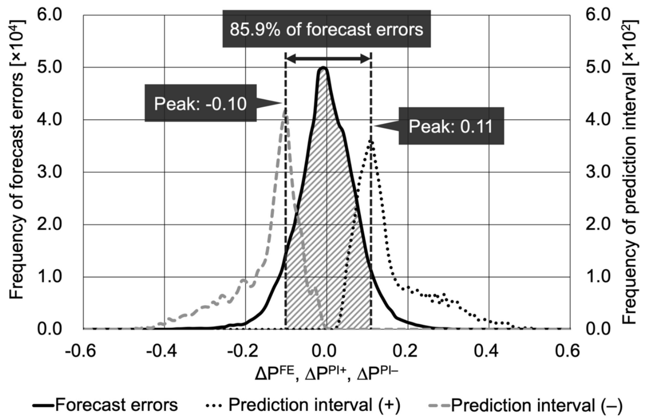


Fig. 2. Frequency of the prediction interval and forecast errors from December 2017 to February 2018. The dotted line indicates the frequency of the prediction interval as differences between forecasts and the 97.5th percentile forecasts. The dashed line shows the frequency of the prediction interval as differences between forecasts and the 2.5th percentile forecasts. Forecast errors shows differences between actual outputs and forecasts. The value of 0 pu indicates that each forecast is the same or actual outputs are equal to the forecasts. The maximum frequency of the prediction interval is shown at 0.10 and 0.11 pu, and 85.9% of forecast errors lie between the two peaks.

B. Data to Use

The forecast data with the 2.5th percentile forecasts and the 97.5th percentile forecasts are generated using a forecast integration method by Takeuchi et al [10]. The forecasts are updated every 30 min, and the time resolution is also 30 min. The forecast horizon is 48h. The 95% prediction interval are defined as the difference between the 2.5th percentile forecasts and the 97.5th percentile forecasts. Thus, the intervals between the two forecasts indicate a 95% probability that actual outputs from WPPs lie within the intervals. The prediction interval are calculated as described in (1) and (2),

$$\Delta P_I^{PI+} = P_I^{FC+} - P_I^{FC} \quad (1)$$

$$\Delta P_I^{PI-} = P_I^{FC-} - P_I^{FC} \quad (2)$$

TABLE I. BASIC METHOD AND PROPOSED METHODS

	SOC Maintenance	Prediction Interval
Basic Method	Not considered	Not considered
Method 1	Considered	Not considered
Method 2	Considered	Considered

The actual output data of the wind farms in the Tohoku region in Japan were used. The total rated output was in the range of 459.38–461.88 MW, and the term of the data was 151 d, from December 2017 to April 2018. The time resolution of the actual output data was 10 s. The value of 1 pu is defined as the total rated output of wind farms. Furthermore, forecast errors were calculated as described in (3).

$$\Delta P_{t_s,I}^{FE} = P_{t_s,I}^{AO} - P_I^{FC} \tag{3}$$

The data were divided into two, data for analysis and data for numerical simulations. The former was the data from December 2017 to February 2018, and the latter was from March 2018 to April 2018. The prediction interval and forecast errors that appear from 1.5 h to 2 h after the forecast update were calculated by (1) and (2) using the data for analysis. The frequency of the prediction interval and forecast errors were recorded every 30 min and every 10 s, respectively. The results of the calculations are depicted in Figure 2. The dotted line indicates the frequency of the prediction interval as differences between the forecasts and the 97.5th percentile forecasts. The dashed line shows the frequency of the prediction interval as differences between the forecasts and the 2.5th percentile forecasts. The maximum frequency of the prediction interval is shown at 0.10 and 0.11 pu, and 85.9% of forecast errors lie between the two peaks.

C. Determination of Bids

This paper proposes and compares three methods for bid determination: the basic method, Method 1, and Method 2. Table I lists the three methods. The basic method does not consider the SOC maintenance and the prediction interval. Method 1 considers only the SOC maintenance, and Method 2 considers both the SOC maintenance and the prediction interval. Details are provided below.

1) Basic method: The bid volumes are the same as the forecasts. The SOC maintenance and the prediction interval are not considered. Figure 3 illustrates the outline of the basic method.

2) Method 1: The SOC of an ESS at the beginning of the ToD is estimated from the SOC at the current time using the difference between the bid volume and the forecast data until the beginning of ToD as described in (4).

$$SOC_{t+3}^{EST} = SOC_t + \frac{\sum_{i=I}^{I+2}(E_i^{BID} - P_i^{FC})}{CP_{rated}} \tag{4}$$

This estimation method was reported in [7]. The target SOC is set as 0.5, and the difference between the estimated SOC and the target SOC was calculated. Thus, the energy required to maintain the SOC can be calculated as described in (5).

$$E_{I+3}^{RQ} = |SOC_{TRG} - SOC_{t+3}^{EST}| \times CP_{rated} \tag{5}$$

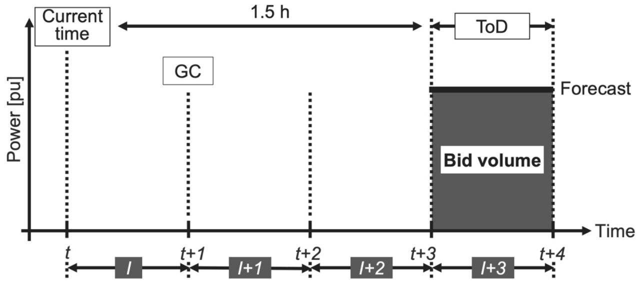


Fig. 3. Outline of the basic method. The bid volume is the same as the forecast. SOC maintenance and the prediction interval are not considered.

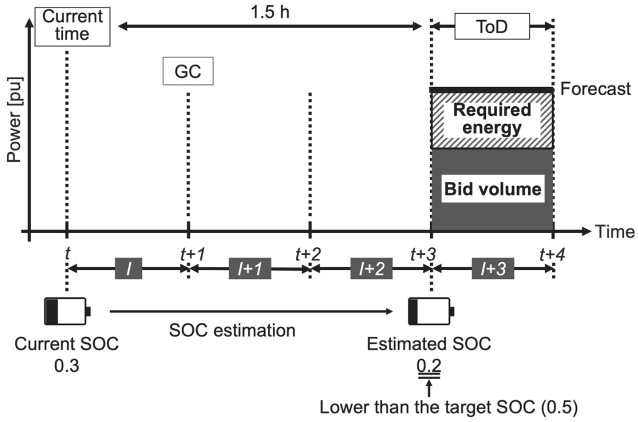


Fig. 4. Outline of Method 1. The SOC at the beginning of ToD is estimated using the SOC at the current time, and the estimated SOC is compared to the target SOC. Forecasted energy is divided into the energy required for the SOC maintenance and the bid volume if the estimated SOC is lower than the target SOC (0.5). Conversely, the energy required to maintain the SOC is added to forecasted energy if the estimated SOC is higher than the target SOC. The upper limit of the required energy is the ESS rated power.

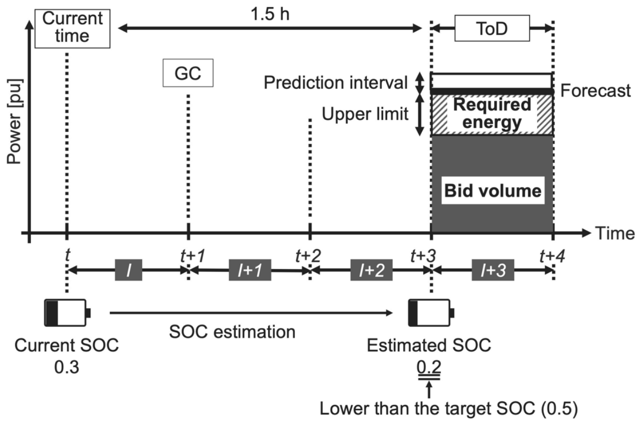


Fig. 5. Outline of Method 2. The process of SOC estimation and calculation of required energy is the same as Method 1. The upper limit of the required energy in Method 1 is the ESS rated power; however, the upper limit in Method 2 is decided as the difference between the rated power and the prediction interval in the ToD. If the ESS must charge or discharge, the prediction interval are reduced to 0.1 or 0.11, respectively.

The required energy is divided by 0.5 to represent a half of an hour, and the power required to maintain the SOC is obtained as described in (6).

$$P_{I+3}^{RQ} = \frac{E_{I+3}^{RQ}}{0.5} \tag{6}$$

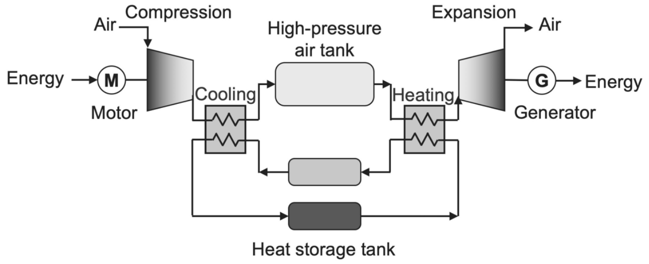


Fig. 6. The structure of the CAES system.

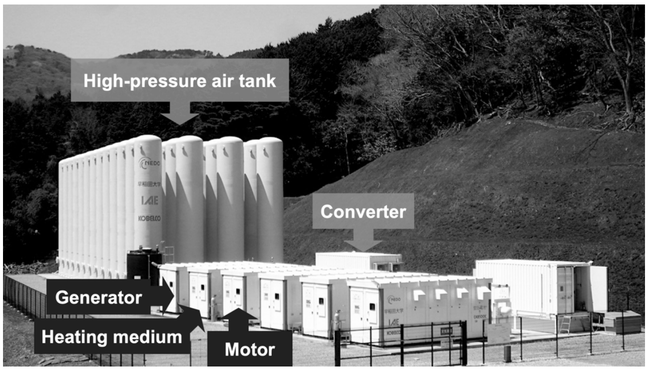


Fig. 7. CAES system in Higashi-izu, Japan.

TABLE II. CONDITIONS OF THE CAES SYSTEM ASSUMED IN THIS STUDY

Rated power [pu]	0.3
Hours to discharge [h]	1.0, 1.5, 2.0, 2.5
Charge efficiency [%]	85.5
Discharge efficiency [%]	71.6
Target SOC	0.5
Rated power [pu]	0.3

However, the required power is reduced to the rated power of the ESS as described in (7) if the required power exceeds the rated power.

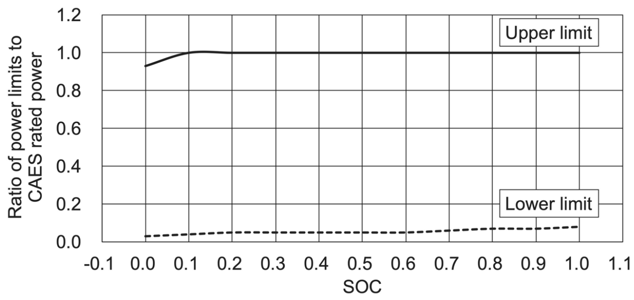
$$P_{I+3}^{RQ} = \begin{cases} P_{I+3}^{RQ}, & P_{I+3}^{RQ} \leq P_{rated} \\ P_{rated}, & P_{I+3}^{RQ} > P_{rated} \end{cases} \quad (7)$$

The bid volume is determined by the required power and forecast as described in (8).

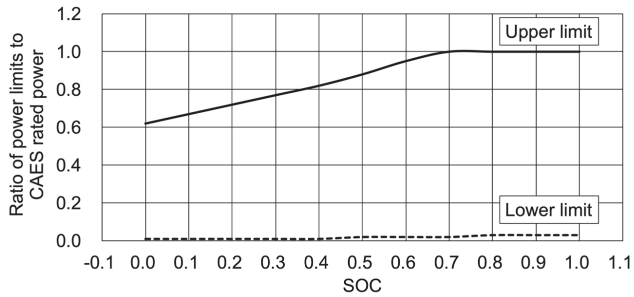
$$E_{I+3}^{BID} = \begin{cases} (P_{I+3}^{FC} - P_{I+3}^{RQ}) \times 0.5, & SOC_{t+3}^{EST} < SOC_{TRG} \\ (P_{I+3}^{FC} + P_{I+3}^{RQ}) \times 0.5, & SOC_{t+3}^{EST} > SOC_{TRG} \end{cases} \quad (8)$$

The bid volume is smaller than the forecast if the ESS must charge, and the bid volume is larger than the forecast if the ESS must discharge. This step is based on the assumption that the actual output of WPPs is equal to the forecast. The outline of the Method 1 is illustrated in Figure 4.

3) Method 2: The upper limit of the required power for the SOC maintenance is the ESS rated power in Method 1 (See (6)), but the ESS cannot use more power than the rated power. Therefore, there is an imbalance if forecast errors occur when the required energy is equal to the ESS rated power. Method 2 uses the prediction interval to reduce the upper limit of the required power for SOC maintenance. The



(a) Ratio of upper and lower power limits in case of charging.



(b) Ratio of upper and lower power limits in case of discharging.

Fig. 8. Ratio of upper and lower power limits to the CAES rated power assumed in this study.

upper limit is determined by the difference between the rated power and the prediction interval in the ToD; however, the limit is adjusted depending on the conditions. Therefore, (9) is adopted if the ESS must charge, and (10) is used if the ESS must discharge.

$$P_{I+3}^{UP} = \begin{cases} P_{rated} - \Delta P_{I+3}^{PI+}, & \Delta P_{I+3}^{PI+} \leq 0.11 \\ P_{rated} - 0.11, & \Delta P_{I+3}^{PI+} > 0.11 \end{cases} \quad (9)$$

$$P_{I+3}^{UP} = \begin{cases} P_{rated} - |\Delta P_{I+3}^{PI-}|, & \Delta P_{I+3}^{PI-} \geq -0.10 \\ P_{rated} - 0.10, & \Delta P_{I+3}^{PI-} < -0.10 \end{cases} \quad (10)$$

The values of 0.10 pu and 0.11 pu indicate the maximum frequency of the prediction interval (see Figure 2). The required power is reduced to the upper limit if the required power exceeds the upper limit.

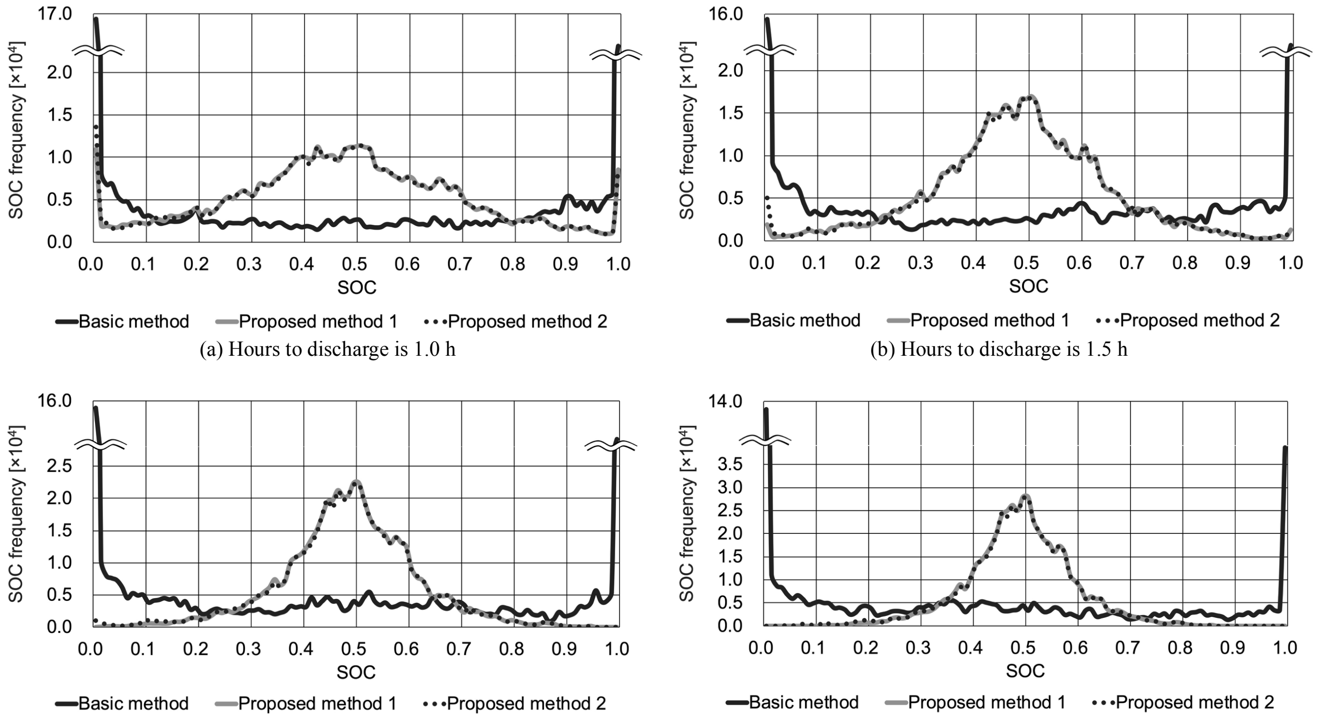
$$P_{I+3}^{RQ} = \begin{cases} P_{I+3}^{RQ}, & P_{I+3}^{RQ} \leq P_{I+3}^{UP} \\ P_{I+3}^{UP_c}, & P_{I+3}^{RQ} > P_{I+3}^{UP} \end{cases} \quad (11)$$

Compared with (7), the required power can be controlled to avoid reaching the rated power in (11). The bid volume was determined by (8). The outline of Method 2 is provided in Figure 5.

III. SIMULATION CONDITIONS

A. Conditions of CAES System

In this study, a CAES system is assumed as an ESS. The CAES system is located in Higashi-izu, Japan. Figure 6 illustrates the CAES system structure, and Figure 7 shows the exterior of the CAES system. The CAES system drives the compressor using energy and compresses air into the tank when electricity is charged. The CAES system expands the compressed air and supplies electricity by operating the generator when electricity is discharged. The conditions of the



(a) Hours to discharge is 1.0 h

(b) Hours to discharge is 1.5 h

(c) Hours to discharge is 2.0 h

(d) Hours to discharge is 2.5 h

Fig. 9. Histogram of SOC frequency every 10 s. The SOCs of Method 1 and Method 2 are maintained approximately 0.5 longer than that of the basic method in all cases.

TABLE III. RESULTS OF TRADES IN 61 D WHEN THE HOURS TO DISCHARGE THE CAES SYSTEM IS 2.0 H

	Basic method	Method 1	Method 2
Total bid volume [pu-h]	433.6	401.0	401.7
Total supplied energy [pu-h]	414.9	401.2	401.6
Positive imbalance [pu-h]	7.29	0.391	0.142
Negative imbalance [pu-h]	-26.0	-0.210	-0.203
Total imbalance [pu-h]	33.29	0.6018	0.3453
The ratio of the imbalance to total bid volume [%]	7.68	0.150	0.0860

CAES system are listed in Table II. Four patterns of hours to discharge the CAES system are prepared, and the rated power of CAES system is set as 0.3 pu at all the hours to discharge. Note that the value of 1.0 pu was defined as the total rated output of wind farms. The charge and discharge efficiencies were assumed to be 85.5% and 71.6%, respectively. The value of the target SOC was 0.5. Moreover, the ratio of upper and lower power limits to the CAES rated power were assumed as shown in Figure 8. These limits depend on the SOC. The process of SOC estimation, charge/discharge by CAES and decision of required power for SOC maintenance considers these limits. The efficiency and limits of power to charge are based on the above assumptions; these values are different from the actual values.

B. Simulation Steps

The bid volume was determined using each method. The actual outputs were compared with the bid volume, and the differences between them were calculated. The differences were adjusted by charging or discharging the CAES system. In the simulation, the values of the SOC were recorded every 10 s. At the end of the simulation, the frequency of the SOC, results of the trades, and imbalance were analyzed and evaluated.

IV. RESULTS

A. Frequency of the SOC

Figure 9 presents the SOC frequency recorded every 10 s. The SOCs of Method 1 and Method 2 were maintained approximately 0.5 longer than that of the basic method in all cases. This result suggests that the SOC maintenance is effective, and the CAES is used efficiently. However, in comparison with Method 1, the SOC of Method 2 tends to stay at approximately 0 longer when the hours to discharge is 1.0 h, 1.5 h, and 2.0 h. Therefore, the effect of SOC maintenance may decrease because the consideration of the prediction interval reduces the energy required to maintain the SOC.

B. Results of Trades

Table 3 presents the results of trades when the hours to discharge the CAES system is 2.0 h. The total bid volume of Method 1 and Method 2 are lower than that of the basic method owing to the SOC maintenance. However, the energy required to maintain the SOC is controlled by considering the prediction interval; therefore, the total bid volume of Method

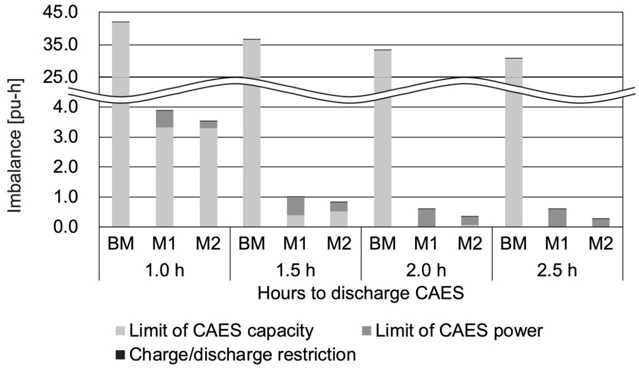


Fig. 10. Imbalances divided into its causes. BM, M1, and M2 denote the basic method, Method 1, and Method 2, respectively. The limit of CAES capacity occurs when the SOC reaching 0 or 1. The limit of CAES power occurs when the difference between the actual output and the bid volume exceeds the CAES rated power. The charge/discharge restriction occurs when the required power is less than the lower limit of the power required to charge (See Figure 8).

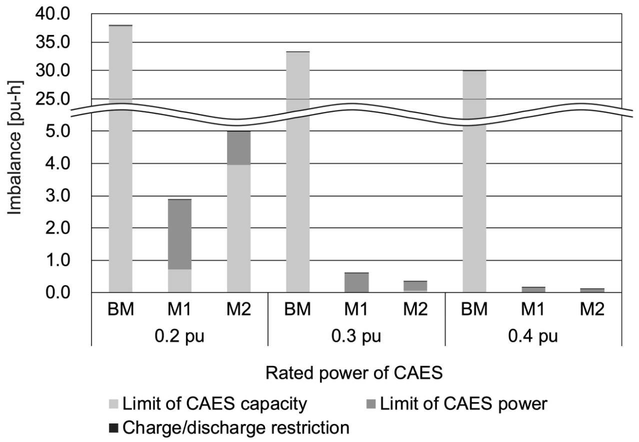


Fig. 12. Imbalances divided into the causes when the hours to discharge CAES are 2.0 h. The total imbalance and imbalance caused by the limit of capacity in Method 2 is higher than those in Method 1 when the CAES rated power is 0.1pu and 0.2 pu. However, the imbalance caused by the limit of power in Method 2 is lower than that in Method 1. The total imbalance in Method 2 is slightly lower than that in Method 1 when the CAES rated power is 0.3 pu because the control of upper limit is suitable for the rated power. Moreover, total imbalances in Method 1 and Method 2 are not different when the CAES rated power is 0.4 pu.

2 is slightly higher than that of Method 1. Furthermore, the degree of total imbalance between the total supplied energy and the bid volume in Method 2 is lower than that in the basic method and Method 1. Thus, SOC maintenance using the prediction interval contribute in reducing the imbalance. Note that the total imbalance was calculated by adding positive imbalance to the absolute value of the negative imbalance. Moreover, the difference between the total bid volume and the total supplied energy is equal to the sum of the positive imbalance and the negative imbalance.

Figure 10 shows the degree of imbalance divided into its causes. BM, M1, and M2 denote the basic method, Method 1, and Method 2, respectively. The limit of CAES capacity occurs when the SOC reaches 0 or 1. The limit of CAES power occurs when the difference between actual output and the bid volume exceeds the CAES rated power. The charge/discharge restriction occurs when the required power is less than the lower limit of power required to charge/discharge (See Figure 8). Figure 10 indicates that the degree of the total imbalance in Method 2 is lower than that of the basic method and Method 1 at all hours to discharge the CAES system. Moreover, the imbalance caused by the limit of CAES capacity hardly increases, although the energy required for SOC maintenance in Method 2 is reduced.

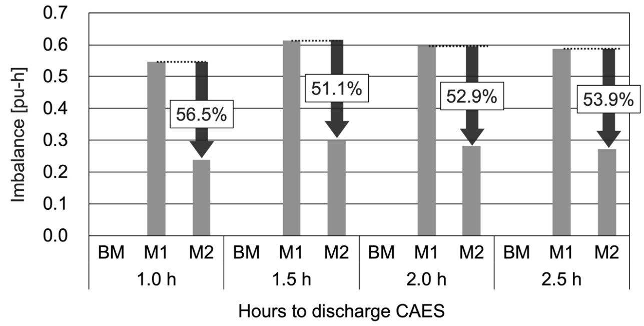


Fig. 11. Imbalances caused by Limit of CAES power.

Figure 11 illustrates the imbalances caused by the limit of CAES power. In comparison with Method 1, Method 2 can reduce the imbalance, and the maximum reduction rate is 56.5%. These results suggest that consideration of the prediction interval is effective to reduce the imbalance.

V. Discussion

In this section, the degrees of imbalance depending on the CAES rated power are discussed. The rated power of CAES is set as 0.2–0.4 pu, and the hours to discharge CAES are fixed as 2.0 h for each CAES rated power.

Figure 12 depicts the imbalances divided into the causes when the hours to discharge CAES is 2.0 h. Figure 12 indicates that the total imbalance and imbalance caused by the limit of capacity in Method 2 is higher than those in Method 1 when the CAES rated power is 0.2 pu. However, the imbalance caused by the limit of CAES power in Method 2 is lower than that in Method 1. These results suggest the control of the upper limit using the prediction interval may be excessive and the energy required for SOC maintenance may be reduced considerably when the CAES rated power is small. Conversely, the total imbalance in Method 2 is slightly lower than that in Method 1 when the CAES rated power is 0.3 pu, because the control of the upper limit is suitable for the rated power. Moreover, total imbalances in Method 1 and Method 2 are not different when the CAES rated power is 0.4 pu. This result suggests that the prediction interval does not affect the reduction of imbalance when the rated power is 0.4 pu.

Therefore, these results indicate the balance of power and hour conditions is important. The selection of the best conditions will be discussed as future tasks.

VI. Conclusion

In this paper, a bid determination method using the prediction interval of forecast was proposed. The method was compared with methods that do not use the prediction interval. Three methods were compared, and the bid volume was the same as forecasts in the basic method. In Method 1 and Method 2, the SOC at the ToD was estimated, and the energy required to maintain the SOC was considered when the bid volume was decided through the determination process. Method 1 uses the rated power of ESS as the upper limit of the required energy to maintain the SOC. Conversely, Method 2 uses the difference between the rated power of ESS and the prediction interval in the ToD as the upper limit. Wind farms with a CAES were considered, and a numerical simulation is conducted. As a result, the proposed method could reduce the degrees of total imbalance and imbalance caused by the excess power between the power required for SOC maintenance and the CAES rated power. Furthermore, the maximum reduction rate of the imbalance caused by the excess power was 56.5%.

In conclusion, considering the prediction interval is effective in reducing imbalance. Therefore, the use of the prediction interval contributes to the development of practical bid determination. In future work, we plan to consider forecast errors for bid volume decision to obtain accurate values of forecast and the prediction interval.

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