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Optimization of Battery Energy Storage System Capacity for Wind Farm with Considering Auxiliary Services Compensation

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Abstract: An optimal sizing model of the battery energy storage system (BESS) for large-scale wind farm adapting to the scheduling plan is proposed in this paper. Based on the analysis of the variability and uncertainty of wind output, the cost of auxiliary services of systems that are eased by BESS is quantized and the constraints of BESS accounting for the effect of wind power on system dispatching are proposed. Aiming to maximum the benefits of wind-storage union system, an optimal capacity model considering BESS investment costs, wind curtailment saving, and auxiliary services compensation is established. What's more, the effect of irregular charge/discharge process on the life cycle of BESS is considered into the optimal model by introducing an equivalent loss of the cycle life. Finally, based on the typical data of a systems, results show that auxiliary services compensation can encourage wind farm configuration BESS effectively. Various sensitivity analyses are performed to assess the effect of the auxiliary services compensation, on-grid price of wind power, investment cost of BESS, cycle life of BESS, and wind uncertainty reserve level of BESS on this optimal capacity.

Keywords: large-scale wind farm; auxiliary services compensation; battery energy storage system; optimal capacity; equivalent loss of cycle life

1. Introduction

As a flexible and adjustable power supply, the energy storage system provides a new idea to cope with the intermittent power integration [1]. In various types of large-scale energy storage systems (such as pumped storage, compressed air storage, etc.), battery energy storage system (BESS) has the most promising broad in power applications benefiting from its high energy efficiency and weak requirement of geographical conditions [2]. Wind farm with BESS configuration will become a common model for large-scale wind power development in the future. However, in addition to the high investment cost of BESS, how to optimal BESS size to balance the investment cost and the effect of levelling wind power fluctuation and uncertainty has been a research hotspot in recent years.

Current research of the optimal storage capacity with adapting to the scheduling plan are mainly focused on the two parts: smoothing the fluctuation of wind output to deal with the wind peaking demand [3–5]; compensating the uncertainty of wind output to make up the wind forecast error [6,7]. In literature [8], an optimization model of BESS aiming to adapt the scheduling plan based on the reference output of wind power during each designated period is proposed. Taking an hour as time-scale, the literature [9] built an optimization capacity model of BESS that is based on the unit commitment. However, the above literatures only consider the fluctuation of wind power at each time window, and not account for the influence of wind power integration on the system peaking and sparing demand. In reference [10], an optimization method of BESS capacity was proposed with taking hourly and inner-hour fluctuation of wind output. By providing some climbing ability, BESS can effectively reduce the addition peaking and sparing demand that is caused by wind power integration. A multi-objective optimization method for BESS configuration and capacity optimization is built in literature [11], and the uncertainty of wind output is added to the model in the form of probability. In [12], the benefit of electricity price on the difference between peak and valley in BESS is added to the optimization model based on the electricity market. In [13], when considering the duration time of BESS reserving the wind power uncertainty, the cost-benefit analysis model of BESS is established based on the optimal power flow. In [14], BESS is used to provide sparing reserve capacity for wind power integration, and it is of great significance to optimize the storage capacity with taking the sparing auxiliary service of BESS into account. All of these research focus on minimizing the cost of BESS investment based on the cost-benefit analysis. However, the above literatures have not analyzed the economy from the point view of wind-energy union system.

Actually, the most direct benefit of wind-energy union system is the additional electricity of wind power integration though transferring the wind power during the hard peaking periods. What is more, BESS can also mitigate the peaking and sparing auxiliary services costs of systems that are caused by the fluctuation and uncertainty of wind power integration, which can be regarded as a certain degree of compensation to the wind energy union system. But, there is little literature to consider such auxiliary service compensation into the optimization storage capacity.

Herein, from the point view of wind-energy storage, this paper puts forward a method to optimize the storage capacity with considering auxiliary service compensation. First of all, the fluctuation and uncertainty of the hourly wind output are analyzed. Based on description of BESS participating in the scheduling plan, the auxiliary service cost of BESS mitigation is quantified. Secondly, the equivalent life loss is introduced by considering the BESS irregular charge and discharge on the impact of cycle life. The BESS constraints adapting to the scheduling plan is put forward. Taking the wind power curtailment as one of decision variable, an optimal capacity model of BESS with considering BESS investment cost, wind curtailment saving, and auxiliary service compensation is built based on the cost benefit analysis. Finally, an example is given to validate the effectiveness of the proposed model, and the influence of the auxiliary services compensation, on-grid price of wind power, BESS investment cost, BESS cycle life, and BESS reserve level on the optimization result is analyzed. Results show that the auxiliary service compensation can effectively encourage the wind farm configuration BESS.

The reminder of this paper is organized, as follows: Section 2 describes the optimization problem of BESS adapting to the scheduling with involved the auxiliary service compensation as one of the benefit of wind-energy union system. Section 3 provides the mathematical formulation of the optimization storage capacity problem. Section 4 presents the case results and Section 5 outlines the conclusions.

2. Problem Formulation

2.1. Wind Output Characteristics

2.1.1. Variability

Considering the wind power as a "negative" load, the net load of systems can be described as Formula (1). With the wind power participating in the scheduling plan, the climbing constraint of conventional units that responds to the peaking requirement of the net load fluctuation can be expressed as Formula (2).

$$P_{net,t} = P_{load,t} - P_{wind,t} \quad (1)$$

$$R_{amp,t}^{dn} \leq P_{net,t} - P_{net,t-1} \leq R_{amp,t}^{up} \quad (2)$$

Depending on the fluctuation magnitude and direction of the wind output and the load demand, the variability of wind output can be divided into positive peaking characteristics and anti-peaking characteristics [15]. Figure 1 shows the typical daily load demand and wind output of an actual wind farm in central China.

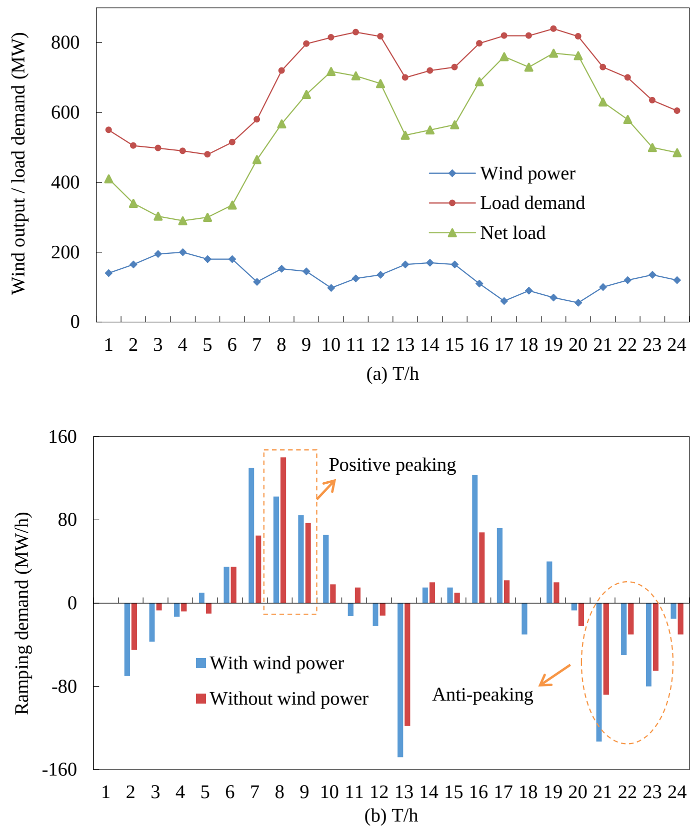

Figure 1. Load demand/wind output under four seasons; (**a**) net load fluctuation with and without wind power integration; and, (**b**) ramping demand of systems with and without wind power.

As we can see from Figure 1, the output of the wind farm exhibits obviously anti-peaking characteristics at most moments, especially at night, when the wind power output is high and the load is small. In which situation, the usual peaking strategy of systems is to on-off peaking units or curtail the wind power to meet the additional peaking demand that is caused by wind power integration, which aggravate the operation cost of conventional units and limit the benefit of wind farm owners at the same time.

2.1.2. Uncertainty

Plenty of statistical analyses of the wind forecast error show that the hourly forecast error of wind output tends to be normal distribution and different wind speed segments appear in different deviation normal distributions [16]. Assuming that the hourly maximum deviation from the mean value is three times to the standard deviation, the prediction interval of wind power can be illustrated in Figure 2 based on the probability density function (PDF) of wind forecast error in literature [17].

Figure 2 shows that the forecast error interval of wind power corrected by the deviation normal distribution is not symmetric with the forecast value, which provides a more accurate spinning reserve information for the wind power participation in the scheduling plan. Unlike the highly repetitive of load demand [18], the wind output has a great range of uncertainty. In order to cope with the uncertainty of wind power, conventional units need to reserve additional climbing ability as the spinning reserve, which is also the main limitation reason for "wind power difficult integration".

The spinning reserve constraint of conventional units with wind power integration can be expressed as Equation (3).

$$\begin{cases} \sum_{i=1}^{N_g} u_{i,t} P_{gi}^{\max} - \sum_{i=1}^{N_g} u_{i,t} P_{gi,t} \geq \Delta P_{load,t} + \Delta P_{wind,t}^{up} \\ \sum_{i=1}^{N_g} u_{i,t} P_{gi,t} - \sum_{i=1}^{N_g} u_{i,t} P_{gi}^{\min} \geq \Delta P_{load,t} + \Delta P_{wind,t}^{dn} \end{cases} \quad (3)$$

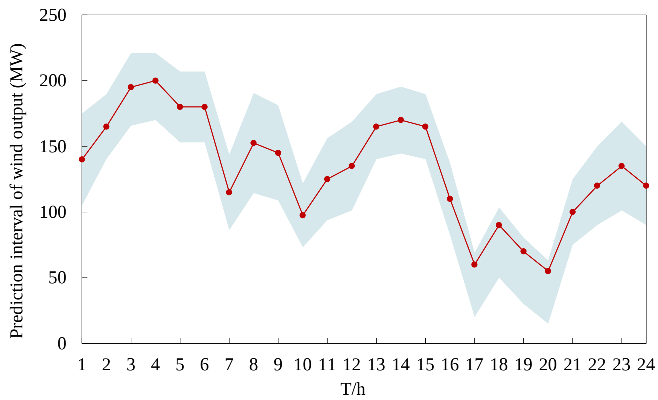

Figure 2. Prediction interval of wind output though a day.

2.2. *Auxiliary Services Eased by BESS*

2.2.1. BESS Participation in the Scheduling Plan

As can be seen in Figure 3, BESS enables wind power controllable by transferring wind power in space and time. Storing wind energy during anti-peaking periods and releasing wind energy during positive-peaking periods are helpful for easing the additional peaking demand of conventional units in tracking wind power fluctuation.

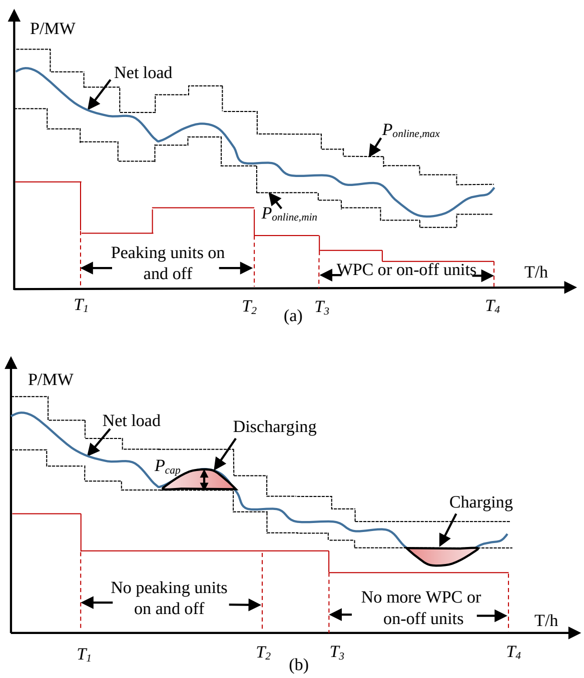

Figure 3. Schematic diagram of battery energy storage system (BESS) participating in the scheduling; (**a**) wind power integration without BESS; and, (**b**) wind power integration with BESS. BEES: battery energy storage system; WPC: wind power curtailment.

As shown in Figure 4, the forecast value of net load is between P_{net} and P'_{net} with considering a certain confidence interval. BESS provides a good choose for wind farm to handle with the forecast error by leaving some reserve capacity. By comparing Figure 4a,b, it is corresponding to the lower peaking capacity of conventional units by increasing BESS reserve capacity P_{cap}, which can effectively improve the economics operation of conventional units.

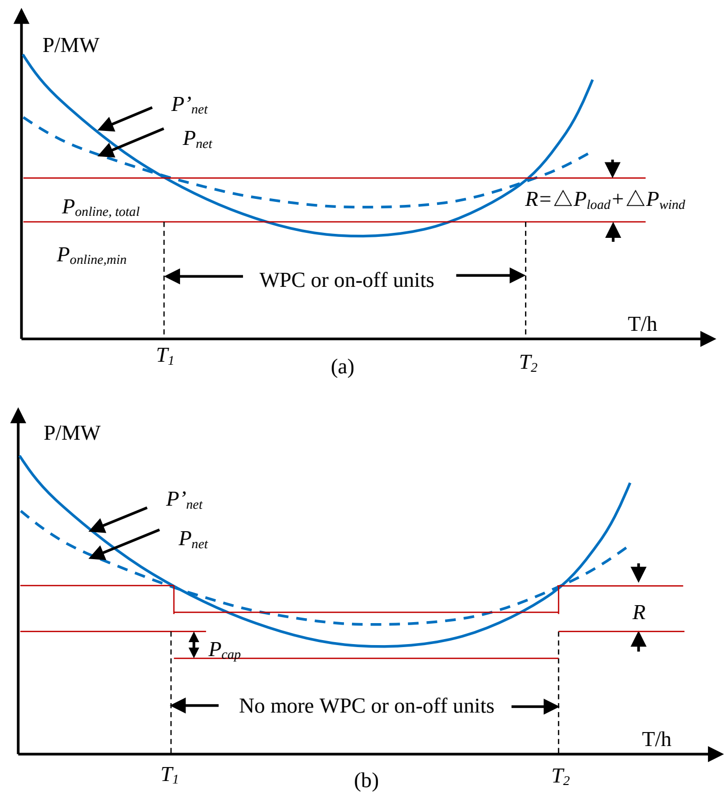

Figure 4. Schematic diagram of BESS making up the sparing reserve of the wind power uncertainty; (**a**) wind power integration without BESS; and, (**b**) wind power integration with BESS.

2.2.2. Quantification the Ancillary Services Cost

The variability and uncertainty of wind power generation require conventional units to provide corresponding auxiliary service support [19]. Above analyses show that the auxiliary services that are provided by conventional units include peaking and spinning reserve two parts. The variability of wind power mainly affects the peaking auxiliary service and the uncertainty of wind power mainly affects the spinning reserve auxiliary service.

This paper defines that the auxiliary service cost of BESS mitigation for wind power integration is the difference between the ancillary services cost provided by conventional units with and without configuration BESS, which can be generally divided into two categories: fixed cost and variable cost. Among them, the fixed cost is mainly the investment cost of the conventional units, the variable cost is the fuel cost [20].

$$C_{serve} = C_{fixed} + C_{vary} \tag{4}$$

$$\begin{cases} C_{fixed} = C_{AI} \cdot (\sum_{i=1}^{M} P_{gi}^{N} - \sum_{i=1}^{M_{BESS}} P_{gi}^{N}) \\ C_{vary} = (c_g^{BESS} - c_g^{Wind}) \cdot \sum_{t=1}^{T} \sum_{i=1}^{M_{BESS}} P_{gi,t}^{B} \end{cases} \tag{5}$$

2.3. Mathematical Description of BESS

There are two key parameters influencing the optimization capacity of BESS: the investment cost and the cycle life. Researches have shown that BESS will be widely used in electricity market with the investment cost being less than 250 \$/kW·h and the cycle life being more than 4000 times [1,2]. At present, the lithium-ion battery is considered to be the most promising energy storage technology for its high rate in the MW-level electrochemical energy storage project [3]. Therefore, this paper chooses the lithium-ion battery as an example to carry out the following research, and the unit investment cost of BESS set as 250 \$/kW·h and the cycle life takes 4500 times.

2.3.1. Equivalent Loss of Cycle Life

The cycle life of BESS is mainly effect by the charge/discharge depth [21]. According to the test results of the Lithium-ion battery system in literature [22], BESS has a corresponding cycle life at each depth of discharge, as listed in Table 1.

Table 1. Relationship between the charge/discharge depth and cycle life of Lithium-ion battery system.

Discharge Depth (%)	0.2	0.4	0.6	0.8	1.0
Cycle (time)	9000	7200	5700	5200	4500

Table 1 shows that shallow charge/discharge depth is conducive to extend the cycle life of BESS. Based on the power function method in Formula (6) [23], the fitting curve of charge/discharge depth with cycle life is illustrated in Figure 5.

$$L_{cyc,D} = 4500D^{-0.795} \tag{6}$$

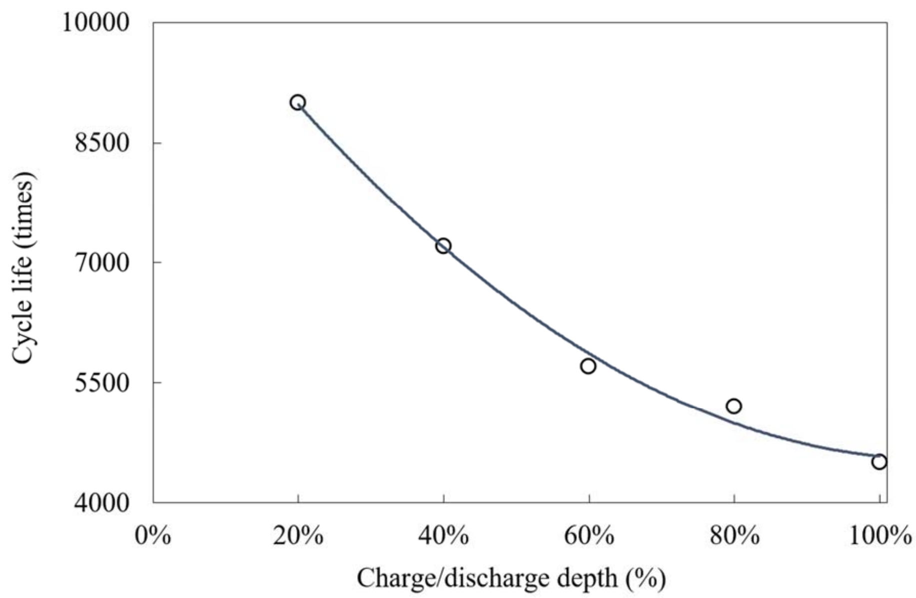

Figure 5. Depth of charge/discharge versus the cycle life of the Lithium-ion battery.

Based on the irreversible electrochemical loss for each charge/discharge process on the cycle life of BESS [24], the equivalent lifetime loss rate is used to obtain the equivalent service year of BESS, calculated as Equation (7):

$$T_{life} = 1/\sum_{i=1}^{N_B} \frac{1}{L_{cyc,Di}} \tag{7}$$

2.3.2. Constraints of BESS Accounting to the Scheduling

The wind-energy union system participating in the scheduling aims to achieve the coordination with conventional units, that is, give full play to BESS on conventional units of the complementary role, while trying to avoid BESS frequent charge and discharge. Generally, the rated power and energy capacity are two key indicators in describing the sizing of BESS [25]. Under the condition of allowing wind power curtailment, the charge/discharge power of BESS can be illustrated as Formula (8):

$$P_{s,t} = P_{wind,t} - P_{union,t} - P_{wloss,t} \tag{8}$$

where, $P_{s,t} > 0$ refers to charging, and $P_{s,t} < 0$ refers to discharging.

The net load of systems with wind-energy union system integration can be rewritten, as follows:

$$P'_{net,t} = P_{load,t} - P_{wind,t} - P_{s,t} \tag{9}$$

The state of charge (SOC) of BESS at hour t can be expressed, as follows:

$$\begin{cases} S_{soc,t} = S_{soc,t-1} + \eta_s P_{s,t} \Delta t, & P_{s,t} > 0 \\ S_{soc,t} = S_{soc,t-1} + \frac{P_{s,t}}{\eta_s \Delta t}, & P_{s,t} < 0 \end{cases} \tag{10}$$

Set λ_t as the charge/discharge status of BESS at time t, and λ_t can only have one state in each time period, that is:

$$\lambda_1, \lambda_2, \cdots \lambda_t \in \{-1, 0, 1\} \tag{11}$$

where, λ_t = 0 means the BESS being the idle float status; λ_t = 1 means the BESS being the discharging status; and, λ_t = 1 means the charging status.

Subject to the limitations of the rated charge/discharge power and rated energy storage capacity of BESS, the constraints of BESS at time t are shown, as follows:

$$\begin{cases} |P_{s,t}| \le \eta_s P_{cap} \\ 0 \le S_{soc,t} \le S_{cap} \end{cases} \tag{12}$$

Equation (12) limit the fluctuation range of wind power in adjacent scheduling intervals, which alleviates the additional peaking demand that is caused by wind power integration. If BESS can keep a certain reserve capacity for the uncertainty of wind output, it will further alleviate the additional spinning reserve requirement. Thus, constraints of BESS that adapting to the scheduling can be expressed as:

$$\begin{cases} -\eta_s P_{cap} + \Delta P^{dn}_{wind,t} \le P_{s,t} \le \eta_s P_{cap} - \Delta P^{up}_{wind,t} \\ \Delta P^{dn}_{wind,t} \Delta t \le S_{soc,t} \le S_{cap} + \Delta P^{up}_{wind,t} \Delta t \end{cases} \tag{13}$$

It should be noted that when BESS provides spinning reserve for wind power forecast error, conventional units only need to reserve the load forecast error, that is, only $\triangle P_{load,t}$ need to be retained in the Equation (3) given in Section 2.1.2.

As shown in Formula (13), the BESS capacity for wind farm will be increased while considering BESS as reserve capacity for the wind uncertainty, which further increases the investment cost of the wind-energy union system. However, the equivalent cycle life of BESS can be expanded under this situation of shallow charge/discharge (detailed analysis shown in Section 2.3.1). It is equivalent to decrease the unit investment cost of BESS among the full cycle life to some extent. In addition, BESS providing the spinning reserve capacity will also receive more additional auxiliary services compensation benefit. Thus, how to reasonably consider the BESS reserve degree for the wind uncertainty is also the problem to be discussed in the following research.

3. Optimal Model

3.1. Objective Function

Based on the cost-benefit analysis, an optimization capacity model of BESS aiming to maximize the net income of wind-energy union system is proposed in this part.

$$\max f = S_{ave} + C_{serve} - C_{ost} \tag{14}$$

(1) Investment cost of BESS C_{ost}

The amortized capital cost model of BESS in [26] is adopted and modified as the cost function to be minimized, where the influences of the depth and times of the charge/discharge on the equivalent loss of cycle life are taken into account. The cost function can be written as:

$$C_{ost} = \frac{C_c(p,n)}{365}(\alpha^s \cdot P_{cap} + \beta^s \cdot S_{cap})$$
$$\begin{cases} C_c(p,n) = \frac{p(1+p)^{T_{life}}}{(1+p)^{T_{life}}-1} \\ \beta^s = \frac{C_E}{T_{life}} + C_{OM} \\ \alpha^s = r \cdot \beta^s \end{cases} \tag{15}$$

(2) Directly benefit of saving wind curtailed energy S_{ave}

Wind power curtailment will be mitigated by BESS shifting this part of energy during wind anti-peaking periods. So that the reduction amount of wind curtailed energy with and without considering BESS can be regarded as the direct benefit of the wind-energy union system. During a scheduling period, it can be expressed as Formula (15):

$$S_{ave} = \rho^w \left(\int_{t=1}^{T} (P_{wloss,t} - P^B_{wloss,t}) \Delta t \right) \tag{16}$$

(3) Additional benefit of auxiliary service compensation C_{serve}

This paper proposes that the auxiliary service cost of wind power integration eased by BESS should be as a part of the revenue of wind-energy union system. Based on the analysis of Section 2.2, the ancillary service costs of the "net load" fluctuation curve with and without BESS can be calculated, as follows:

$$C_{serve} = C^{Wind}_{serve} - C^{BESS}_{serve} \tag{17}$$

3.2. Constraints

Other constraints including the wind curtailment constraint, unit output constraint, climbing constraint, and on/off time constraint, are still traditional constraints and not discussed in this paper.

$$s.t \begin{cases} P^{\min}_{gi} \le P_{gi,t} \le P^{\max}_{gi} \\ 0 \le P_{wloss,t} \le P_{wind,t} \\ 0 \le \left| P_{gi,t} - P_{gi,(t-1)} \right| \le R_i \\ \begin{cases} (u_{i,t} - u_{i,(t-1)})[T^{\text{on}}_{i,(t-1)} - T^{\text{on}}_{i,\min}] \le 0 \\ (u_{i,(t-1)} - u_{i,t})[T^{\text{off}}_{i,(t-1)} - T^{\text{off}}_{i,\min}] \le 0 \end{cases} \end{cases} \tag{18}$$

3.3. System Performance Indices

The following performance indices related to the economics of conventional units and wind farm are used to compare different cases in the model.

(1) Unit coal cost of conventional units ($/MW·h) c_g

$$\begin{cases} c_g = C_{Gen} / \sum_{t=1}^{T} \sum_{i=1}^{N_g} P_{gi,t} \\ C_{Gen} = \sum_{t=1}^{T} \sum_{i=1}^{N_g} [u_{i,t} f(P_{gi,t}) + u_{i,t}(1 - u_{i,(t-1)}) S_i] \\ f(P_{gi,t}) = a_i + b_i P_{gi,t} + c_i P_{gi,t}^2 \end{cases} \tag{19}$$

(2) Wind energy curtailment rate (%) q

$$q = \int_{t=1}^{T} P_{wloss,t} \Delta t / \int_{t=1}^{T} P_{wind,t} \Delta t \times 100\% \tag{20}$$

4. Case Study

4.1. Basic Data

Taking the 10 units system as example, shown in Table 2. The installed capacity of wind farm selected from the North China is 250 MW, and the forecast value of wind power and load during a scheduling period are shown in Figure 1. The forecast error interval of wind power is shown in Figure 2. Since the charge/discharge efficiency of the lithium-ion battery is high, η_s is regarded as 1.0. r set as 1.172, and the C_{OM} is taken as 26 $/kW·h/year [24]. The on grid price of wind power ρ^w is 0.084 $/kW·h (0.54 ¥/kW·h). The computation for all cases are carried out using YALMP toolbox and CPLEX solver [27].

Table 2. Parameters of 10 units system.

Units	1	2	3	4	5	6	7	8	9	10
P_{max} (MW)	455	455	130	130	162	80	85	55	55	55
P_{min} (MW)	150	150	20	20	25	20	25	10	10	10
c ($/h)	1000	970	700	680	450	370	480	660	665	670
b ($/MW·h^2)	16.19	17.26	16.60	16.50	19.70	22.26	26.74	25.92	27.27	27.29
a (10^{-3} $/MW·h^2)	0. 48	0.31	2.0	2.1	3.98	7.12	7.9	4.13	2.22	1.73
R_i (MW/h)	130	130	60	60	90	40	40	20	20	20
S_i ($)	4500	5000	550	560	900	170	260	30	30	30
Initial status (h)	8	−8	−5	−5	−5	−3	−3	−1	−1	−1

4.2. Operation Results Without BESS

In order to provide a basis for the subsequent calculation of the wind power curtailment and the auxiliary service cost mitigation by BESS, scheduling results of systems without BESS are given in Table 3. The dispatch output of each conventional unit and the wind curtailed energy during a scheduling period are descripted in Figure 6.

- Case 1: The optimal scheduling results of systems without wind power integration is calculated.
- Case 2: With allowing wind power curtailment, the scheduling results with wind power integration is considered.

While comparing case 1 with case 2 in Table 3, due to its anti-peaking characteristics and uncertainty of wind output, the unit coal cost of conventional units is significantly increased from 21.221 $/MW·h to 21.534 $/ MW·h, and the total installed capacity of conventional units participating in auxiliary service is also increased by 55 MW. Figure 6 shows more intuitively that due to the limitation of the minimum output of conventional units, a large amount of wind power curtailment occurs at 2:00 to 6:00 during the difficult peaking period with high wind output and low load demand.

Table 3. Scheduling results of systems with and without wind power integration.

Case	c_g ($/MW·h)	q (%)	$\sum P_{gi}^{N}$ (MW)
1	21.201	-	382
2	21.579	6.09%	437

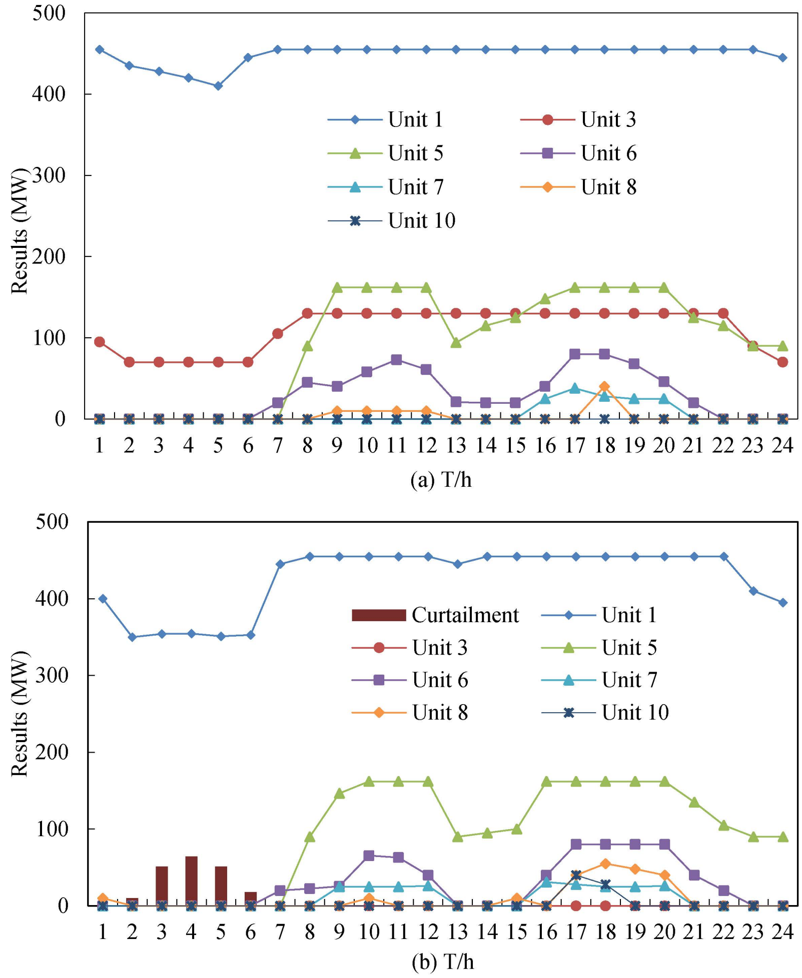

Figure 6. Scheduling results of systems without BESS; (**a**) Case1 results without wind power integration; and, (**b**) Case 2 results with wind power integration.

4.3. Operation Results with BESS

Based on the proposed optimization model (Case 3), the effect of auxiliary service compensation benefit and BESS reserve wind uncertainty on optimal capacity are analyzed, as below in Table 4. The charge/discharge power and SOC of BESS under different cases over a scheduling period are described in Figure 7.

- Case 3: both the auxiliary service compensation and BESS reserve wind forecast error are considered, that is, the proposed model;
- Case 4: without auxiliary service compensation and with BESS reserve wind uncertainty;
- Case 5: with auxiliary service compensation, and without BESS reserve wind uncertainty; and,
- Case 6: neither auxiliary service compensation nor BESS reserve wind uncertainty is considered.

It should be noted that, the objective functions of Case 4 and Case 6 without considering the auxiliary service compensation will be rewritten as:

$$\max f = S_{ave} - C_{cap} \quad (21)$$

Table 4. Optimal results with BESS for different cases.

Case	c_g (\$/MW·h)	f (\$)	q (%)	P_{cap} (MW)	S_{cap} (MW·h)	N_{cyc} (time)
Case 3	21.238	2990	0.0%	58	122.4	1.73
Case 4	21.305	−1540	0.64%	55	88.9	1.71
Case 5	21.290	1790	3.61%	27.75	60.25	1.85
Case 6	21.544	1050	4.32%	7.15	35.75	1.56

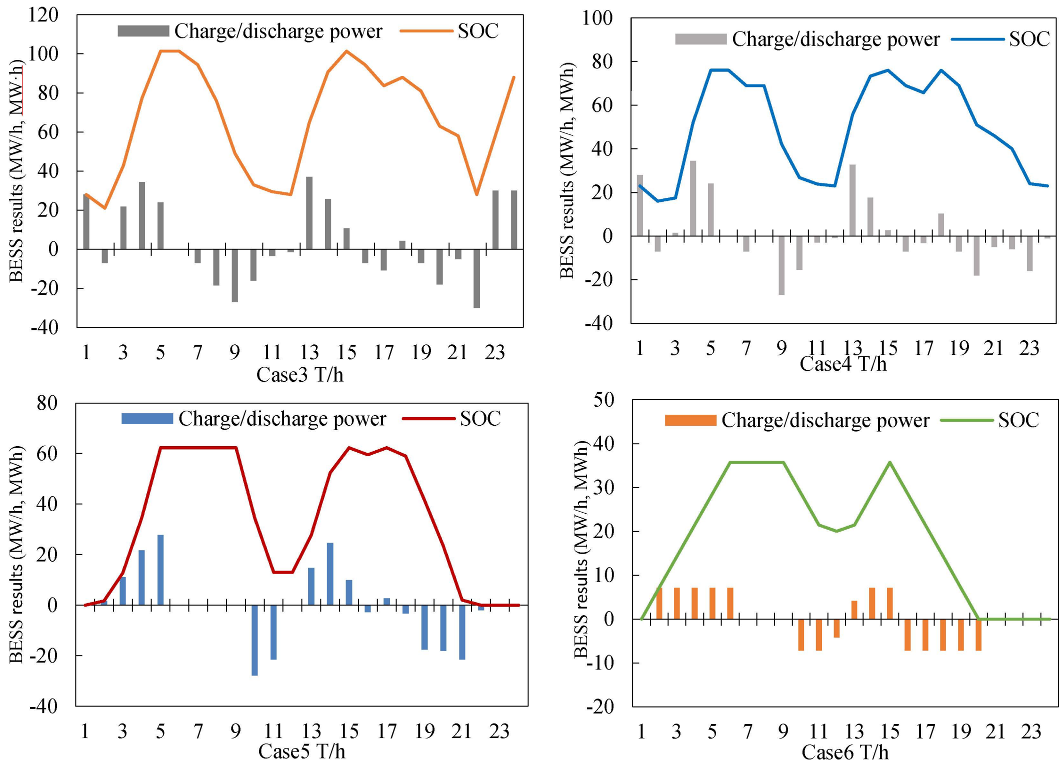

Figure 7. Charge/discharge process of BESS under different cases. SOC: state of charge.

(1) Table 4 shows that with configuring BESS, c_g of Case 3~Case 6 with BESS is significantly smaller than that of case2 without BESS (21.534 \$/MW·h). It is reasonable that BESS mitigate the operational cost of conventional units caused by the wind anti-peaking characteristics through transferring the wind power in the time and space. c_g of the proposed model Case 3 (c_g = 21.236 \$/MW·h) is close to the results of Case 1 without wind power integration. It means that with taking both the ancillary services compensation and BESS reserve wind uncertainty into account, wind-energy union system can achieve the "wind power friendly integration" and the economy operation of systems.

(2) Comprising c_g of Case 3 with Case 4 in Table 4, it can be seen that the economical operation of conventional units is further improved with BESS keeping reserve capacity for the wind uncertainty. From the benefits f of the wind energy union system in the Case 4, it can be seen that even if the unit investment cost of BESS is assumed as 250 \$/kWh, the positive income will not be realized without considering the ancillary services compensation for BESS. That is, ignoring this part benefit of the BESS adapting to scheduling will seriously hinder the enthusiasm of wind farm configuring BESS and further harmful to the large-scale wind power integration.

(3) As the optimal results in Case 5 shows, the total benefit of wind-energy union system is less than the proposed model of Case 3. It is mainly due to the equivalent cycle number over a scheduling period is increased without considering BESS reserve wind uncertainty, which shortens the equivalent cycle life of BESS and equivalent increases the unit investment cost of BESS to some extent. That is, ignore the reduced capacity cost investment of BESS reserve wind uncertainty is not enough to make up for the loss of benefits caused by shorter cycle life in Case 5, which can be more intuitively seen from comparing the charge/discharge process of Case 5 with Case 3 in Figure 7.

(4) Comparison Case 5 with Case 6 in Table 4, it can be seen that a smaller storage capacity is configured in Case 6 without considering the auxiliary service compensation. It is because that the investment cost of BESS is too expense and not enough to be covered by the benefit of additional wind power integration. The wind farm chose to configure less storage capacity for the pursuit of the maximum benefit, which is more clearly pointed in the charge/discharge process during a scheduling period of Case 6 in Figure 7. Thus, the net load fluctuation of systems is not significantly improved and the operational costs c_g is also failed to be improved in Case 6.

4.4. Sensitivity Analysis

4.4.1. On-grid Price of Wind Power

There are differences in on-grid price of wind power for different wind sources. Therefore, the effects of different on-grid price from 0.084 $/kW·h to 0.064 $/kW·h on the optimal storage capacity of BESS are studied, as shown in Table 5.

Table 5. Optimal results under different on-grid prices of wind power.

On-Grid Price ($/kW·h)	f ($)	P_{cap} (MW·h)	S_{cap} (MW·h)
0.084	2990	58	122.4
0.080	2321	54	102.4
0.076	1845	35.25	63.25
0.072	740	27.75	60.25
0.068	322	7.15	14.25
0.064	0	0	0

From Table 5, it can be seen that the capacity of BESS has changed slowly and only reflects on the net benefit of the wind-energy union system before the on-grid price down to 0.076 $/kW·h. However, when the on-grid price of wind power falls to 0.064 $/kW·h, the benefit that is contributed by wind energy union operation cannot balance the investment cost of BESS, and it is no longer suitable for configuring BESS in this wind farm.

4.4.2. Investment Cost and Cycle Life of BESS

As shown in the above analysis of Case 3, wind-energy union system can achieve positive returns under the condition of C_E being 250 $/kW·h and $L_{cyc,N}$ being 4000 times. In other words, the additional benefits for wind farm configuration BESS is greater than the additional investment costs. To find the balance point of the additional benefits and costs with C_E and $L_{cyc,N}$ varying, the impact of C_E and $L_{cyc,N}$ on the optimization results is shown in Figures 8 and 9, respectively.

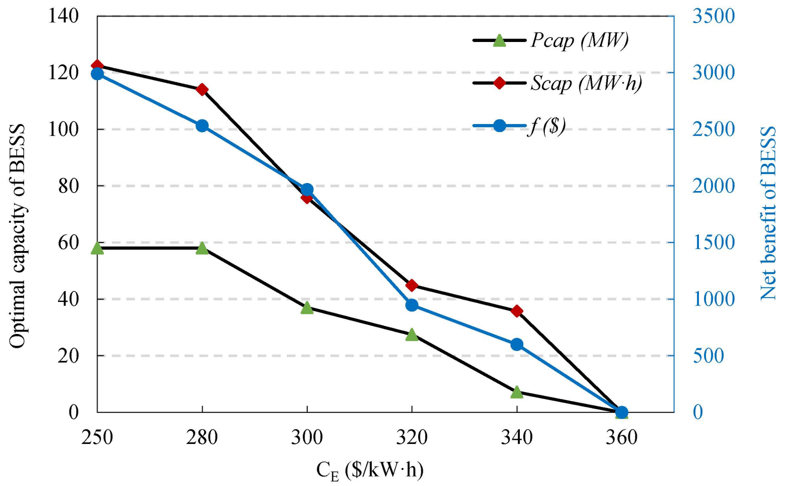

Figure 8. Optimal results under different investment costs of BESS. C_E: unit capacity cost of BESS.

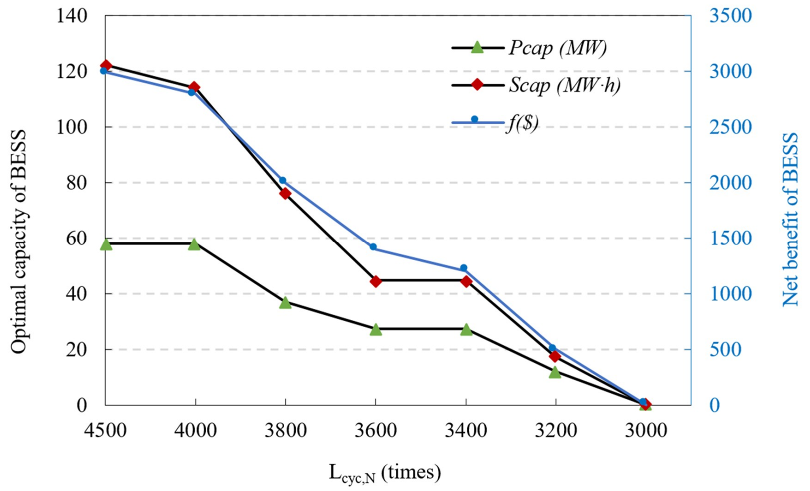

Figure 9. Optimal results under different cycle life of BESS. $L_{cyc,N}$: cycle life of BESS with fully charge/discharge.

(1) It can be seen from Figure 8 that under the condition of $L_{cyc,N}$ being 4000 times, if BESS can be provided a certain compensation for participating in the scheduling, the wind-energy union system will reach the payment balance with C_E being 360 \$/kW·h. That is to say, C_E < 360 \$/kW·h can guarantee the positive benefits of this wind farm. The auxiliary service compensation for BESS is more effective to stimulate the wind farm configuring BESS and promote the early arrival of the "BESS generation".

(2) Similarly, from Figure 9, we can see that the capacity of BESS is *0* when $L_{cyc,N}$ reducing to 2800 times under the condition of C_E = 250 \$/kW·h. In other words, compared to the above mentioned in Section 2.3, the cycle life should being more than 4000 times in large-scale BESS application, it will be more effective to incentive wind farm configuring BESS with taking the auxiliary service compensation of BESS into account.

4.4.3. Reserve Level of BESS

As mentioned earlier, the forecast error of wind power can be described by a normal distribution with a certain mean and standard deviation. That is, the forecast error interval concentrates in the larger probability of the inter-range. If considering the full reserve by the costly BESS for the 100% confidence interval of wind forecast error, there may be some reserve idle with less economical. Therefore, it is necessary to analyze the influence of the reserve level of BESS on the optimal capacity. The reserve level of BESS in Case 3 and Case 5 can be regarded as 100% and 0%. Based on Case 3 with the 100% reserve level, the reserve level is shortened successively. Thus, the effect of different reserve levels on the optimization results is analyzed, as shown in Table 6.

It is worth mentioning that, in order to ensure that the reserve capacity that is provided by conventional units and BESS meet the uncertainty of wind output, the BESS constraints and spinning reserve constraint of units can be rewritten as:

$$\begin{cases} -\eta_s P_{cap} + \Delta P^{dn}_{wind,t} \leq S_t \leq \eta_s P_{cap} - \varepsilon_s \Delta P^{up}_{wind,t} \\ \Delta P^{dn}_{wind,t} \Delta t \leq S_{soc,t} \leq S_{cap} + \varepsilon_s \Delta P^{up}_{wind,t} \Delta t \end{cases} \tag{22}$$

$$\begin{cases} \sum\limits_{i=1}^{N_g} u_{i,t} P^{\max}_{gi,t} - \sum\limits_{i=1}^{N_g} u_{i,t} P_{gi,t} \geq \Delta P_{load,t} + (1-\varepsilon_s) \Delta P^{up}_{wind,t} \\ \sum\limits_{i=1}^{N_g} u_{i,t} P_{gi,t} - \sum\limits_{i=1}^{N_g} u_{i,t} P^{\min}_{gi,t} \geq \Delta P_{load,t} + (1-\varepsilon_s) \Delta P^{dn}_{wind,t} \end{cases} \tag{23}$$

Table 6. Optimal results under different reserve level of BESS.

ε_s	c_g ($/MW·h)	f ($)	q (%)	P_{cap} (MW·h)	S_{cap} (MW·h)
100%	21.238	2990	0.0%	58	122.4
80%	21.324	3160	1.10%	44.8	95.2
60%	21.323	3930	1.84%	34.8	79.6
40%	21.312	3560	2.54%	31.2	70.35
20%	21.307	2910	3.23%	29.5	61.25
0%	21.290	1790	3.61%	27.75	60.25

As can be seen from Table 6, with decreasing the BESS reserve level for wind uncertainty, the net benefit of wind-energy union system returns to increase first and then decrease. This is mainly because that the investment cost of BESS is still expensive when compared to the benefit of auxiliary service compensation. If BESS provides full reserve capacity for the wind uncertainty, there will be a lot of waste for the wind uncertainty being mostly concentrated in the small confidence interval with high probability. However, with the reserve level decreasing, the net benefit of wind-energy union system decreases again limited by the equivalent cycle life and the auxiliary service compensation income.

In addition, it can be seen from Table 6 that, when the reserve level being 60%, both the net benefit of wind-energy union system and the operation efficiency of conventional units are the maximum. The variety rates of the performance indices (f, c_g, and q) are small with the reserve level between 40% and 60%. It means that the installed power of BESS being 68.75–76.8 $/MW·h and the installed capacity of BESS between 30.2 and 32.8MW can realize the operation efficiency of BESS and conventional units in this wind farm.

5. Conclusions

In this paper, a novel method that determines the optimal BESS capacity with considering auxiliary services compensation is proposed from the point view of wind-energy union system. By quantifying the auxiliary services cost that is caused by the variability and uncertainty of wind output and analyzing the effect of irregular charge/discharge process on the life cycle of BESS, both the auxiliary services compensation and the equivalent loss of the cycle life are introduced in this model, which is more reasonable and precise in economic and electrochemical sense. Simulation results shows that the auxiliary services compensation can encourage wind farm configuration BESS effectively.

Moreover, effect of the on-gird price of wind power, investment cost of BESS, cycle life of BESS and BESS reserve level are assessed though sensitivity analyses. Results show that BESS can be early applied in large-scale wind farm with investment cost being less than 360 $/kW·h or the cycle life being more than 2800 times with taking the auxiliary services compensation into account. It is noteworthy that the net income of wind-storage system reach maximum with the reserve interval of BESS being about 40%~60% of the wind power forecasting error.

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Abbreviations

$P_{net,t}$	net load of systems with wind power integration in hour t
$P_{load,t}$	forecast value of load demand in hour t
$P_{wind,t}$	forecast output of wind farm in hour t
$R_{amp,t}^{up}/R_{amp,t}^{dn}$	up/down ramp demand of the net load in hour t
$P_{gi}^{\max}/P_{gi}^{\min}$	maximum/minimum output of unit i
$u_{i,t}$	on-off state of unit i in hour t
$P_{gi,t}$	output of unit i in hour t
$\triangle P_{load,t}$	spinning reserve demand of the load demand in hour t
$\Delta P_{wind,t}^{up}/\Delta P_{wind,t}^{dn}$	upper and down limitation of wind prediction interval
N_g	number of conventional units
$P_{online,max}/P_{online,min}$	upper/lower limitation of the online units
$P_{online,total}$	total output of the online conventional units
P'_{net}	net load of systems with wind farm configuration BESS
R	total spinning reserve capacity required by the system
P_{cap}	rated power of BESS
S_{cap}	rate capacity of BESS
C_{serve}	difference auxiliary service cost of systems with and without BESS
C_{fixed}	fixed cost item of auxiliary service
C_{vary}	variable cost item of auxiliary service
C_{AI}	daily investment cost per capacity of conventional units
P_{gi}^{N}	rated power of the conventional unit i
$P_{gi,t}^{B}$	output of unit i with configuration BESS in hour t
M^{BESS}/M	number of units participating the auxiliary service with/without BESS
c_g^{BESS}/c_g^{Wind}	unit coal cost of conventional units with/without BESS
T	one scheduling period
D	charge/discharge depth of BESS
$L_{cyc,D}$	cycle life of BESS under the charge/discharge depth of D
$L_{cyc,N}$	cycle life of BESS with fully charge/discharge
N_B	charge/discharge number of BESS though the life cycle
T_{life}	equivalent operation years of BESS
$P_{s,t}$	output of BESS in hour t
$P_{union,t}$	output of wind energy union system in hour t
$S_{soc,t}$	state of charge (SOC) of BESS in hour t
$\triangle t$	scheduled interval
λ_t	charge/discharge status of BESS at time t
η_s	charge/discharge effectiveness of BESS
C_{ost}	total investment cost of BESS
S_{ave}	directly benefit from saving wind curtailed energy
$C_c(p,n)$	capital recovery factor with annual interest rate p
C_E	unit capacity cost of BESS
C_{OM}	unit operation and maintenance cost of BESS
α^s	amortized power cost per year
β^s	amortized capacity cost per year
r	kW·h/kW cost ratio of BESS

ρ^w	on-grid price of wind power
$P_{wloss,t}/P^B{}_{wloss,t}$	curtailed wind energy with and without BESS in hour t
$C_{serve}^{Wind}/C_{serve}^{BESS}$	auxiliary service cost caused by wind power with/without BESS
R_i	ramping ability of unit i
$T_{i,\max}^{\text{on}}/T_{i,\min}^{\text{on}}$	maximum/minimum online time of unit i
C_{Gen}	operating cost function of conventional units
$f(P_{gi,t})$	quadratic fuel cost function with coefficients a_i, b_i, c_i
S_i	on-off cost of unit i
q	curtailed rate of wind power
N_{cyc}	equivalent cycle numbers of BESS though a scheduling period
ε_s	reserve level provided by BESS for the uncertainty of wind power

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