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Energy Storage System Sizing Based on a Reliability Assessment of Power Systems Integrated with Wind Power

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Abstract: The available capacity is a major factor that influences the reliability contribution of energy storage in power systems integrated with wind power. This paper presents the capacity value of the energy storage metrics to quantitatively estimate the contribution of energy storage to the generation adequacy. A method in accordance with EFC approach has been introduced to model the capacity value of energy storage. The adequacy-oriented model of the energy storage available capacity is proposed for the energy storage system, regarding the roles of the key parameters for the CVES analysis. The case study results indicate that the capacity value of energy storage quantitatively weigh the contribution of the energy storage to system reliability. The sensitivity analysis of the impact factors for the CVES is conducted.

Keywords: generation adequacy; capacity value; energy storage system; wind power

1. Introduction

The utilization and development of distributed generators to satisfy electrical load demands has received considerable attention in the last decade. Generation adequacy is utilized to weigh the ability of the available supply capacity to satisfy the load demand. Owing to the fast increase in installed distributed resources, such as wind turbines and energy storage systems, researchers have become more concerned about power system reliability and its economics [1] after the distributed resources are integrated to the system.

Energy storage is a promising technology for improving the generation adequacy of a power system integrated with intermittent energy, and also brings challenges to the security and reliability of the microgrid [2]. Regarding the time scale, the role of an energy storage system (ESS) is recognized either for reliability improvement [3], or for smoothing the fluctuations of the intermittent energy output [4,5]. The energy storage system can respond by suppressing the changes caused by wind and photovoltaic power. Therefore, allocating the capacity of energy storage system is a fascinating challenge to achieve better performance [6–8].

Capacity value is the metric typically used to quantify the contribution of generation on system reliability and for long-run resource adequacy planning [9]. Capacity value is often estimated using reliability-based methods [9]. In these studies, the chronological method and the probability method are used. In addition, the two methods have preferred solutions for different people within the power grid. System operators mainly use the chronological method, while system planners use the probability method [10]. For the probabilistic method, there are four typical capacity value definitions [11], i.e., the equivalent firm capacity (EFC) [12,13], equivalent conventional power plant [10,14], effective load carrying capability (ELCC) method [15–18] and guaranteed capacity. The EFC and ELCC methods are the two most commonly used methods [19].

With respect to the assessment of the contribution of generation devices to the reliability of a power system, current work is mainly centered on intermittent energy such as wind power [3]. Besides, with the solar power as a not negligible part of the power supply, the capacity value of the photovoltaics [20] and the concentrated solar power [14] are also investigated. The studies are concerned with modeling the capacity value of wind power and photovoltaics themselves [15,21]. However, energy storage, for its part, also makes important contributions to the generation adequacy in a power grid. Many factors influence the contribution of the energy system to the grid. First, the characteristics of energy storage systems have added complexity to this problem. In addition, with the development of interactive smart grids, peak loads on power grids can be shifted to off-peak hours using distributed optimization and control solutions [22,23]. Demand side management ultimately influences the energy storage allocation demand [24–26]. Therefore, the contribution of energy storage is often over-estimated, if the contribution has been simply measured by the installed capacity of the energy storage.

Thus far, there has been no comprehensive framework to quantitatively assess the energy storage available with a capacity metric. Furthermore, no developed method has been proposed to systematically evaluate the available capacity for energy storage and consider the influencing factors and parameters. On these premises, intent on how to develop an assessment model to measure the contribution of energy storage to the generation adequacy of a power grid, the authors have worked out an assessment method to quantitatively assess the available capacity of energy storage, providing a basic method for planners to allocate the energy storage capacity. This paper presents a novel and comprehensive framework to evaluate the available energy storage capacity, which effectively establishes a bridge between the reliability contribution and installed capacity for energy storage. The key contributions of this systematic framework include the following:

(1) Introduction of the definition of the capacity value of energy storage (CVES) metrics, in terms of the available capacity; the renewable energy-oriented available capacity metrics are extended to access the energy storage system generator adequacy contribution. Moreover, new CVES metrics are defined to quantify the energy storage that can displace the generation capacity.
(2) The adequacy-oriented models of the energy storage available capacity. In addition to the CVES metrics, an assessment model is proposed for the energy storage system, regarding the roles of the key parameters for the CVES analysis.
(3) An algorithm based on a cooperative equivalent firm capacity to evaluate the CVES metrics in detail by applying this framework to the CVES. Two case studies provide general insights into the CVES concept with different influencing factors.

The rest of this paper is organized as follows: Section 2 presents the definition, the model and the solution of the CVES. Then, the load model, the energy storage model and the wind power model related to the CVES calculation are illustrated in Section 3. The proposed method is applied in the test system IEEE-RTS in Section 4, and the influencing factors of the CVES are analyzed. Finally, the sensitivity analysis is provided.

2. Capacity Value of Energy Storage

The energy storage system stores the surplus energy to satisfy the load demand when power shortages occur, and it effectively improves the generation adequacy. This section describes the definition of CVES. The value of storage from the capacity value is utilized to weigh the capacity contribution of energy storage devices to the generation adequacy. To better improve the system reliability, the energy storage devices are installed near the wind farm in this paper, as shown in Figure 1.

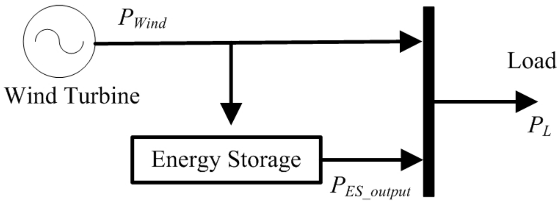

Figure 1. Schematic diagram of the wind-integrated system with energy storage.

2.1. Definition of the Capacity Value of Energy Storage

The CVES represents the equivalent capacity of energy storage that is utilized to satisfy the load demand in a power system. The energy offering mode of energy storage devices is different from that of wind turbines. Energy storage improves the generation adequacy by storing conventional energy sources to satisfy the added load demand. In addition, CVES also describes the capacity of the load demand satisfied by peak load shifting of the energy storage system with the same reliability index.

The reliability index of a power system is correlated to the added installed capacity (conventional power plants, wind turbines and energy storage devices) and the added load under the condition of the invariable load curve and generator capacity. The index measures the effect on the supply adequacy of a power plant with different properties and load demands. Thus, the contributions of different types of power plants to the supply adequacy can be assessed by the index.

According to the well-known Baleriaux–Booth formula [27], the corresponding equivalent load duration curve (ELDC) is as follows, considering the influence of the installed energy storage on the generation adequacy:

$$f^{ES}(x) = p_{kES} f^0(x) + q_{kES} f^0(x - C_{ES}) \tag{1}$$

where $f^0(x)$ is the original load duration curve and C_{ES} is the capacity of the installed energy storage. In addition, q_{kES} is supposed to be the probability that the output power of the energy storage is 0, and p_{kES} is given by $p_{kES} = 1 - q_{kES}$.

The output power of an energy storage system is related to its stored energy and the load level of the power system. When the wind power is sufficient to satisfy the load demand or only the minimum energy is stored in the energy storage devices, the output power of energy storage is 0.

Then, the expression of LOLP is given by:

$$LOLP_{ES} = P(E_k > C_w + C_{ES}) = f^{ES}(C_w + C_{ES}) \tag{2}$$

where E_k is the equivalent load and C_w is the output power of the wind turbines.

To obtain the equivalent capacity of the energy storage system, it is supposed that a unit is installed instead of storing energy in the power system. Therefore, considering the influence of the added unit on the generation adequacy, the corresponding ELDC is:

$$f^C(x) = p_{kC} f^0(x) + q_{kC} f^0(x - C_x) \tag{3}$$

where $f^0(x)$ is the original load duration curve and C_x is the capacity of the added unit. In addition, p_{kC} is the forced outage rate of the unit, and q_{kC} is defined as $q_{kC} = 1 - p_{kC}$.

Thus, the expression of LOLP is given by:

$$LOLP_C = P(E_k > C_w + C_x) = f^C(C_w + C_x) \tag{4}$$

From Equation (4), we can obtain a value of C_x that satisfies the following:

$$LOLP_{ES} = LOLP_C \tag{5}$$

The value of C_x that achieves Equation (5) represents the capacity value of the added energy storage system without changing the shape of the load duration curve. Hence, the capacity value of the energy storage (CVES) presented in this paper can be defined as:

$$f^{ES}(C_w + C_{ES}) = f^{C}(C_w + CVES) \tag{6}$$

It can also be given by:

$$P(P_L > P_{Wind} + P_{ES\_output}) = P(P_L > P_{Wind} + CVES) \tag{7}$$

In Equation (7), P_{Wind} is the total output power of the wind turbines installed in this power system. The variable P_{ES_output} is the output power of the energy storage system.

The calculation of CVES is based on certain reliability criteria. Therefore, the factors that affect the reliability of the power grid also affect the storage value through the capacity value. According to Equation (7), the characteristics of the wind turbine, load demand and energy storage system will affect the CVES.

In this paper, the CVES represents the supply adequacy added in the system with the same reliability index after the energy storage devices are installed. The CVES is a value to quantitatively measure the influence of the added energy storage on the generation adequacy.

2.2. EFC Method for Calculating the Capacity Value of Energy Storage

In a traditional reliability evaluation, a forced outage of the generating unit is one of the main causes of a power supply shortage. After the integration of a wind turbine, the intermittent characteristics of wind power are an additional important cause of a power shortage.

There are many approaches of different equivalent ways to calculate the value of storage using the capacity value. From the perspective of the power supply, the CVES represents the conventional power plant capacity that can be replaced by an energy storage system. From the load perspective, the CVES is the load capacity that is supplied by the added energy storage system.

The equivalent firm capacity (EFC) method is one of the common methods for capacity value assessment. In this paper, the EFC is utilized to calculate the value of storage from the capacity value. After the energy storage devices are installed, the equivalent firm capacity of G_{EFC} is defined as the capacity of a unit, when maintaining the same *HLOLE* without changing the load duration curve. Furthermore, the added firm capacity is the evaluation measure for the system reliability, and the total load rejection hours are the reliability index.

In the previous studies, the LOLP [28,29] and LOLE [30–33] were mainly utilized as the power system reliability indexes to assess the generator capacity adequacy [19,34]. However, the power supply mode of energy storage is different from conventional generators. The output power of the energy storage system is affected by the status of the energy storage devices during the previous time step. Thus, the time interval of the wind speed and the reliability index are the same. In this paper, an hourly loss of load expectation (*HLOLE*) is presented as the reliability evaluation index for the CVES assessment. The time interval of the *HLOLE* is 1 h. The *HLOLE* represents the number of hours during which the generators cannot meet the load demand in a given period n. It is calculated by:

$$HLOLE = \sum_{i=1}^{n} P_i(G_i < L_i) \tag{8}$$

where n is the total number of hours of the given period, P_i $(G_i < L_i)$ is the load loss probability at hour i, and the value of P_i is given in Table 1.

Table 1. Load loss probability for different system statuses.

System Status	Load Loss Probability
The load demand is lower than the power supply	0
Other conditions	1

Before the energy storage devices are installed, the original system integrated with intermittent energy has a certain generation adequacy. After the energy storage is added, the power supply system can satisfy more load demands. The generation adequacy of the power system is improved, and the added generation adequacy is supplied by the installed energy storage. To quantitatively represent the capacity value of energy storage, the EFC method is utilized in this paper.

The capacity value of energy storage indicates the equivalent capacity that replaces the added energy storage while maintaining the same value of *HLOLE*.

After energy storage is added, to calculate the value of the EFC of G_{ES}, the $HLOLE_0$ of the system can be given by:

$$HLOLE_0 = \sum_{i=1}^{n} P_i(G_i + P_{ES\_output,i} < L_i) \tag{9}$$

After the firm capacity, G_{EFC}, replaces the added energy storage, the $HLOLE_f$ of the system is calculated by:

$$HLOLE_f = \sum_{i=1}^{n} P_i(G_i + G_{EFC} < L_i) \tag{10}$$

The capacity of the unit, G_{EFC}, is adjusted until:

$$HLOLE_f = HLOLE_0 \tag{11}$$

The G_{EFC} that satisfies Equation (11) is the capacity value of the added energy storage. Therefore, the value of storage from the capacity value can be calculated by:

$$\sum_{i=1}^{n} P_i(G_i + P_{ES\_output,i} < L_i) = \sum_{i=1}^{n} P_i(G_i + CVES < L_i) \tag{12}$$

where G_i is the output power of the generators at hour i, $P_{ES\_output,i}$ is the output power of the added energy storage at hour i, L_i is the load demand at hour i, and n is the number of hours in the time periods considered in this equation.

Thus, the CVES in Equation (12) is the capacity value of energy storage.

2.3. The Algorithm Flowchart for the Capacity Value Based on the EFC Method

This algorithm is used for calculating the value of storage from the capacity value on the basis of the EFC method and encompasses calculation process of the reliability index. Furthermore, for this analysis, the calculation of reliability index is needed, before and after the energy storage devices are installed. The calculation flowchart of the value of storage from the capacity value based on the EFC method is shown in Figure 2.

The algorithm developments of *CVES* are detailed as follows:

(1) Input the data of the original power system, such as the load level, the wind speed, the wind turbine model and related parameters, and the energy storage model and related parameters.
(2) Calculate the load loss probability of the wind-integrated system at hour i, after the energy storage is added.
(3) Calculate the $HLOLE_0$ of the power system integrated with wind power within the time period using Equation (9). When the load demand is larger than the available capacity at hour i, the

$HLOLE_0$ is accumulated. In addition, when the load demand is smaller than the available capacity, the value of $HLOLE_0$ remains the same.

(4) Save the value of $HLOLE_0$ of the wind-integrated power system with energy storage devices.

(5) Replace the capacity of the energy storage system with the firm capacity.

(6) Adjust the value of the firm capacity, C_{EFC}.

(7) Calculate the load loss probability of the wind-integrated system at hour i, after the firm capacity is added.

(8) Calculate the value of the $HLOLE_f$ of the power system integrated with wind power within the time period using Equation (10).

(9) Check whether Equation (11) is met.

(10) If Equation (11) is not met, return to step (6) to adjust the value of the firm capacity; if Equation (11) is met, then the value of the $HLOLE_0$ is equal to $HLOLE_f$. In addition, the value of the firm capacity is equal to the capacity value of energy storage.

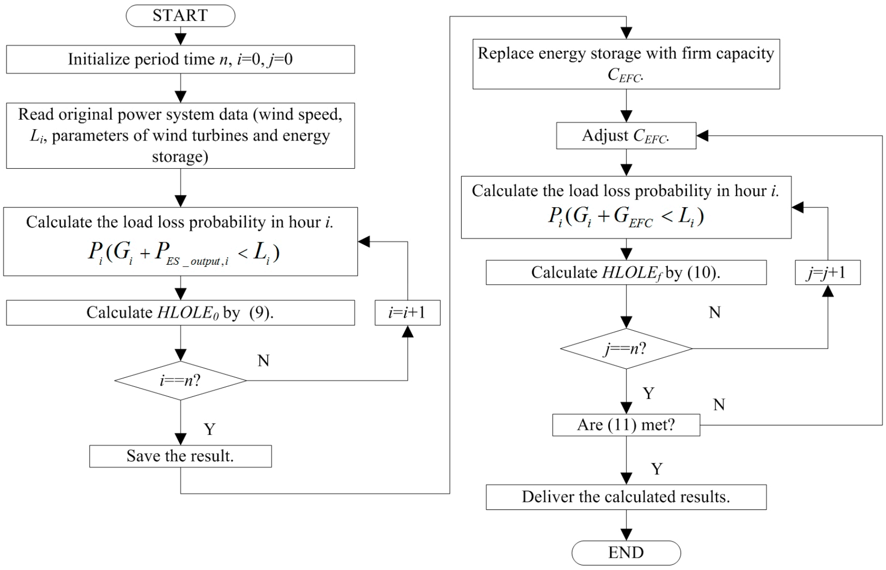

Figure 2. The CVES calculation flowchart.

2.4. Communication System

For this study, the proposed algorithm can be used by system planners to allocate the capacity of energy storage to make the full use of renewable energy. The calculation process is finished offline. The model of practical system is set up for the calculation, and each scheme can be verified. However, for engineering application, the power of wind turbines, the load demand, the SOC and available energy of the energy storage system change every next hour, thus an excellent communication system is an important part in the evaluation tool. To ensure the real time of this communication, it is possible for big areas having multiple ESS, and the area has to be divided into small units.

To control the operation and management of area units, a local energy management system is needed for each area unit to which data will be sent [2]. The information received by the central control unit includes the fuel power, value of predicted renewable power, load management and the value of stored energy in the battery in the previous time. The main goal of the local energy management system is to ensure that the customer demand is met at all times, allocate the dispatchable load demand and maximize the utilization of the available renewable resources.

A central controller is needed to be responsible for the overall coordination [35]. It collects the general properties of each area units [35,36]. The controller can make the required decisions for energy exchange within the area units to decrease production or increase consumption in situations when there is a surplus of electricity in the system based on offer prices [35]. The communication system is addressed in detail in [2,13].

3. System Models

The models for the load, wind power, energy storage and communication system are established in this section to analyze the CVES in the power system integrated with intermittent energy.

As the reserve power supply of the intermittent power, energy storage effectively improves the generation adequacy by peak load shifting. Meanwhile, the factors that influence the output power of energy storage include the output characteristics of the intermittent generator, the characteristics of the load, and the control strategy for energy storage. In addition, the available output power of energy storage at hour (h + 1) is correlated to the energy stored in the energy storage system at hour h; thus, time-sequential models are utilized below.

3.1. Modeling Load

The load models are approximate results of the actual facilities. To assess the CVES, an hourly load model is used to describe the actual load demand. The IEEE-RTS load model [30] and constant load model [30] are also utilized to analyze the effect of the load demands on the CVES. Data for the weekly peak loads as a percent of the annual peak load, a daily peak load cycle as a percent of the weekly peak and weekday and weekend hourly load models for each of the three seasons are provided in the IEEE-RTS load model. We can determine the load value at every hour according to the three parts.

Otherwise, to minimize the production costs and the market clearing prices and to improve the utilization of renewable energy resources, optimal operation programming of electrical systems has been proposed. To reach this goal, energy management systems have been studied in many research studies. Moreover, a demand response expands customer participation in power systems and results in a paradigm shift from conventional to interactive activities in power systems due to the progress of smart grid technology [23]. Meanwhile, the power consuming behavior of users has been directed by the adjustment of the load management electricity structure. During power shortages, the users are prompted to reduce their electricity load. When the available capacity is abundant, users are encouraged to maximize the use of electricity so that the load curve is smoother for achieving the purpose of peak-load shifting.

3.2. Modeling the Wind Power

The wind power output is related to the wind speed and the wind turbine parameters. The ARMA model [32,33,36] and Weibull model [29,30] have been widely used to model the wind speed. The parameters of these wind speed models are estimated using historical data.

A wide range of wind speed data was obtained from data measured during a long period in the same area, in [35]; the historical data cover a long span of time and are used for the wind speed characteristic analysis. The wind speed output probability model is estimated by the cluster of the wind speed history data. The yearly historical chronological wind speed data are directly utilized to describe the wind power model in this paper.

According to the wind speed, the output can be divided into four ranges, including the input speed, output speed and rated speed [30].

The output power of a single wind turbine can be calculated as:

$$P_{Wind} = \begin{cases} 0, & 0 \leq v < C_{in} \\ P_r(C_1 + C_2 v + C_3 v^2), & C_{in} \leq v < C_{rate} \\ P_r, & C_{rate} \leq v < C_{out} \\ 0, & C_{out} \leq v \end{cases} \tag{13}$$

In this study, 10-year-old historical wind speed data from Prince Albert in Canada is adopted. Based on the wind speed data, Figure 3 describes the probability distribution of the wind speed, while Figure 4 shows the wind power probability of a single wind turbine for each year.

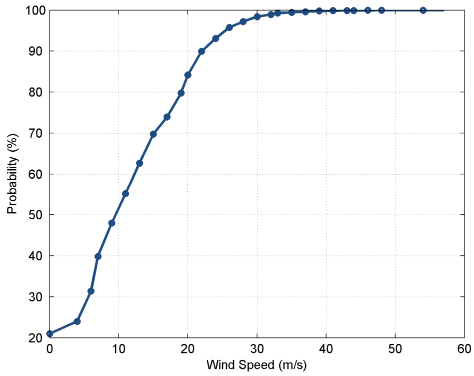

Figure 3. Cumulative distribution curve of the wind speed.

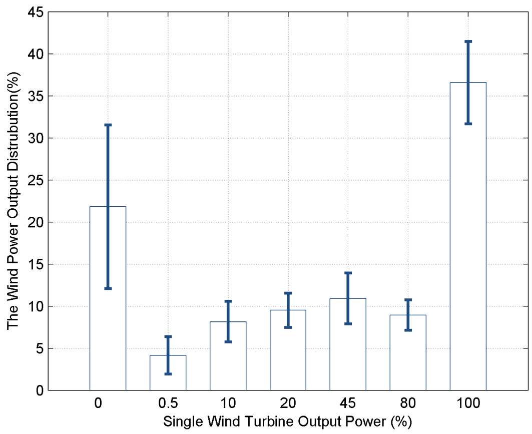

Figure 4. The single wind turbine output power probability.

3.3. Modeling the Energy Storage

Intermittent energy, such as wind and photovoltaic energy, is considerably influenced by environmental conditions with intermittent factors that decide when the intermittent energy is unstable energy for output. The energy storage is capable of effectively providing reserve energy during power supply shortages due to the intermittency of the power.

The model of the energy storage system includes the control approach, energy stored approach and maximum available power. The contribution of the stored energy to the power supply adequacy is dependent on the output power of the stored energy, the restricted and maximum permission charging power, the surplus power of energy storage and its operation strategy. Their relationship is described as:

$$P_{ES\_output} = f(P_{Status\_cha}, P_{Status\_discha}, E_{Bat}, P_{Available}) \tag{14}$$

Therefore, the output power of the stored energy is constrained by the output power of the wind generator, the power differences between the loads and the maximum energy allowed. In addition, it is related to the control strategy [32] and the status and the output function of the energy storage. It is limited by the energy limitations and the output energy limits of the stored energy.

The output power of the energy storage system is also affected by its failure rate. The energy storage battery module is composed of a series of parallel batteries and a battery management system [37]. With regard to the grid connected battery energy storage system, the components are classified as a series system for reliability analysis. The power conversion system is an important component of the grid-connected energy storage system. Therefore, the failure rate of the grid-connected battery energy storage system is related to the failure rate of the energy storage and the power conversion system. In this paper, it is assumed that the failure rate is λ_{bat}, and the repair rate is μ_{bat}.

3.3.1. Charging and Discharging

Intent on the reliability assessment of the wind-integrated power system with energy storage, a simple control approach is utilized in this model without considering the energy price, operational reserve opportunities, etc. [38].

To clearly discuss the CVES, the energy storage system is set near the wind turbines, to carry out charging with the full use of wind power. Once the wind power is no longer sufficient to satisfy the load demand, the stored energy in the ESS will be utilized to afford the demand. The operation strategies for energy storage are stated as follows. When the wind power is able to satisfy the load demand ($P_{Wind} - P_L \geq 0$) at hour i, the ESS stores the remainder of the electric energy from the power grid, and when the wind power cannot satisfy the load demand ($P_{Wind} - P_L \leq 0$) at hour i, the energy storage supplies power back to the grid.

Thus, the amount of charging power of the stored energy at hour h is:

$$P_{Status\_cha} = \begin{cases} P_{EScha\_Max}, & P_{Wind} - P_L \geq P_{EScha\_Max} \\ P_{Wind} - P_L, & P_{EScha\_Max} \geq P_{Wind} - P_L \geq 0 \end{cases} \tag{15}$$

The amount of discharging power of the stored energy at hour h is:

$$P_{Status\_discha} = \begin{cases} P_{Wind} - P_L, & 0 \geq P_{Wind} - P_L \geq -P_{ESdischa\_Max} \\ -P_{ESdischa\_Max}, & -P_{ESdischa\_Max} \geq P_{Wind} - P_L \end{cases} \tag{16}$$

The variables P_{EScha_Max} and $P_{ESdischa\_Max}$ are the constraints on the charging and discharging power of the stored energy. The maximum charging and discharging power should not exceed these values.

3.3.2. Energy Stored in the Energy Storage System

The energy stored in the energy storage system is a piecewise function related to the power status of the ESS. The energy of the ESS at a certain time is related to the energy of the previous time step. The output energy of the ESS is calculated as:

$$E_{output}(h+1) = \begin{cases} E_{output}(h) + TP_{ES\_output}, & E_{\min} \leq E_{output}(h) + T^{-1}P_{ES\_output} \leq E_{\max} \\ E_{\min}, & E_{output}(h) + T^{-1}P_{ES\_output} \leq E_{\min} \\ E_{\max}, & E_{\max} \leq E_{output}(h) + T^{-1}P_{ES\_output} \end{cases} \tag{17}$$

where E_{max} is the highest energy stored in the energy storage system. The stored energy should not exceed E_{max}. In addition, E_{min} is the constraint for the lowest energy stored in the ESS, that is, the stored energy should not be lower than E_{min}. The variable T represents the sampling period. Compared to other time periods, the response time of the battery energy storage is very small; thus, it is negligible in this model [39].

Furthermore, the rated capacity of the energy storage system is relative to the reference temperature. The maximum discharge capacity, the maximum charge/discharge current and the working life of the energy storage system will change with the ambient temperature [40].

Figure 5 shows the relationship between the temperature and the charge/discharge factors [37]. The charge/discharge factors in Figure 5 are the maximum charge and discharge current, respectively. The maximum charge and discharge current changes with the changing of the ambient temperature.

According to Figure 5a, if the temperature is in the range of 0–30 °C, the charging current maintains the rated value. When the temperature increases to the range of 30–40 °C, the charging current of the battery rapidly increases to 0. Furthermore, the battery cannot be charged when the temperature is higher than 40 °C. In addition, according to Figure 5b, the discharge current is the rated value when the temperature is in the range of 0–40 °C. In addition, if the temperature is in the range of −20–0 °C and 40–60 °C, the discharge current of the battery changes with temperature linearly. In particular, it is not advisable to discharge the battery if the temperature is in the range of less than −20 °C or more than 60 °C.

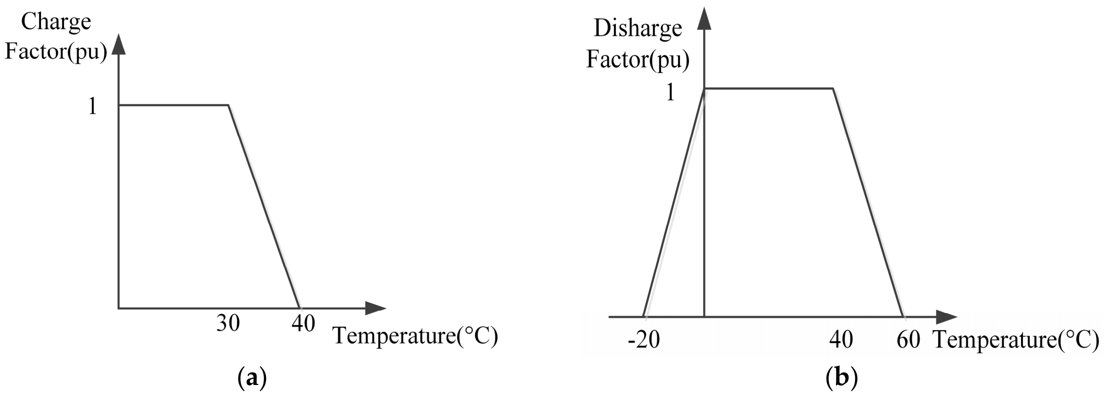

Figure 5. (**a**) Effect of temperature on the maximum charge current; and (**b**) effect of temperature on the maximum discharge current [40].

The charge/discharge capacity is also related to the temperature [40]. The reference temperature is 25 °C. Therefore, the percentage factor of the charge capacity is 100% under the reference temperature. When the ambient temperature is 5 °C lower than the reference temperature, the capacity of the battery decreases nearly by 5% [40]. When the temperature decreases to 0 °C, the capacity of the battery decreases to 75%.

3.3.3. Available Power of Energy Storage

The charging and discharging power of the energy storage system is affected by the different values of the wind power and load. The available power from the energy storage system can be described by:

$$P_{Available}(h+1) = \begin{cases} T^{-1}(E_{output}(h) - E_{\min}), & T^{-1}(E_{output}(h) - E_{\min}) \le P_{ESdischa\_\max} \\ P_{ESdischa\_\max}, & T^{-1}(E_{output}(h) - E_{\min}) \ge P_{ESdischa\_\max} \end{cases} \quad (18)$$

The available power of the energy storage at hour $h + 1$ is related to the output energy at hour h and the sampling period T. The variable $P_{ESdischa\_max}$ is the constraint of the maximum discharging power of the stored energy, and the available power should not exceed this constraint.

3.3.4. Charging Power Period of Energy Storage

The main process of charging includes two stages, constant current charging and constant voltage charging. Figure 6 gives a typical charging curve of batteries. As Figure 6 shows, in the initial stages of charging process, the charging voltage rises until to the set power value. The charging process is changed to constant power charging until to make the SOC of batteries to a certain value. Then it is changed to constant voltage charging. State of charge (SOC) is the remaining capacity of a battery. In the process of charging, we need to take notice of the SOC of energy storage to avoid overcharging.

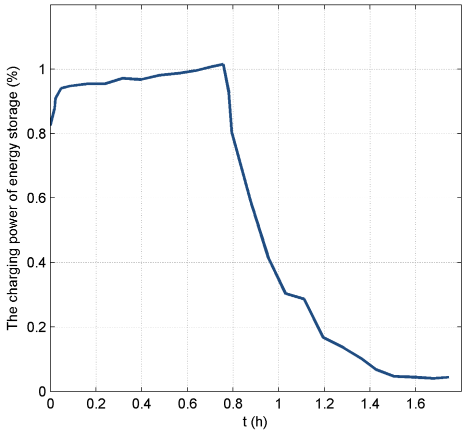

Figure 6. Charging curve of energy storage device.

In this paper, the sampling period is set to be 1 h. Therefore, as Figure 6 shows, the charging power can be approximately regarded as the rated power of ESS.

4. Simulation Results

4.1. System Analysis

The capacity assessment of the energy storage system contribution to the power supply is examined by applying the IEEE-RTS [41] and RBTS [42]. The studied system comprises wind turbines, a power unit and energy storage system (a battery in this study). The wind turbines are located where the wind speed is the same as that in Prince Albert in Canada from year 2001 to 2012. The wind speed data can be found on a Canadian website [43]. The rated wind power is 1000 kW. The energy storage system is installed near a wind farm. The peak yearly peak power is 1800 kW, and the capacity of fuel generator is 1000 kW. The SOC initial value is set at minimum value.

The proposed method for estimation CVES value is implemented in MATLAB 7.0 platform and executed with G2030 CPU, 3.0 GHz desktop computer. The calculations with different discharge power employ the same maximum iteration settings (is set to 15,000 iterations). The algorithm is explained in the following including execution time of the algorithm and the CVES related to different P_{discha_max}. The CCVE value and the computation time of the proposed algorithm with different discharge power are maintained in Table 2. The execution time increases with the increase of discharge power of energy storage system. However, the proposed algorithm can be finished in a few seconds. Therefore, the proposed algorithms should be able to fulfill this requirement in a short period.

Table 2. The CVES of energy storage with different discharge power.

P_{chmax}	P_{dchmax}	*CVES*	Execution Time (s)
250	200	199	13.109
300	250	245	13.890
350	300	293	14.500
400	350	332	15.454
450	400	380	15.672
500	450	424	16.719
550	500	460	17.156
600	550	489	17.438

As shown in Table 2, the CVES value of energy storage is closely related to the discharge power of energy storage system. The CVES values are approximately equal to the discharge power of EES, when the capacity is lower than 300 kW. This means that the ESS is fully used to feeding the load demands at this working status. When the capacity keeps on increasing, the CVES values are less than the installed capacity. This is means that the adding capacity of ESS plays a minor role in improving the reliability of system. As a result, by this way, less expenses will be paid for feeding them by consumers.

The aggregate hourly average load demand and available output power in the power system is presented in Figure 7a, and the charging/discharging status is presented in Figure 7b during 24 h time interval. As observed, the wind turbine is faced with a shutdown during 19:30–23:00 and 0:00–6:00 periods and the ESS is also faced with a shutdown during 11:00–14:00 and 15:00–19:00 periods as shown in Figure 7. As seen in Figure 7b, all of the available power by ESS has been used in algorithm during 11:00–12:00, 14:00–15:00 and 19:00–23:00 periods. During the 0:00–8:00, 11:00–14:00 and 15:00–19:00 of the system operation, ESS is always operated in charging mode. In the method, ESS is operated about 67% period in charging mode and 33% in discharging mode during 24 h of system operation. During the 11:00–14:00 and 15:00–18:00 periods, the wind power is abundant to feeding the load demand and to charging the ESS, and the wind power curtailment occurs during the periods.

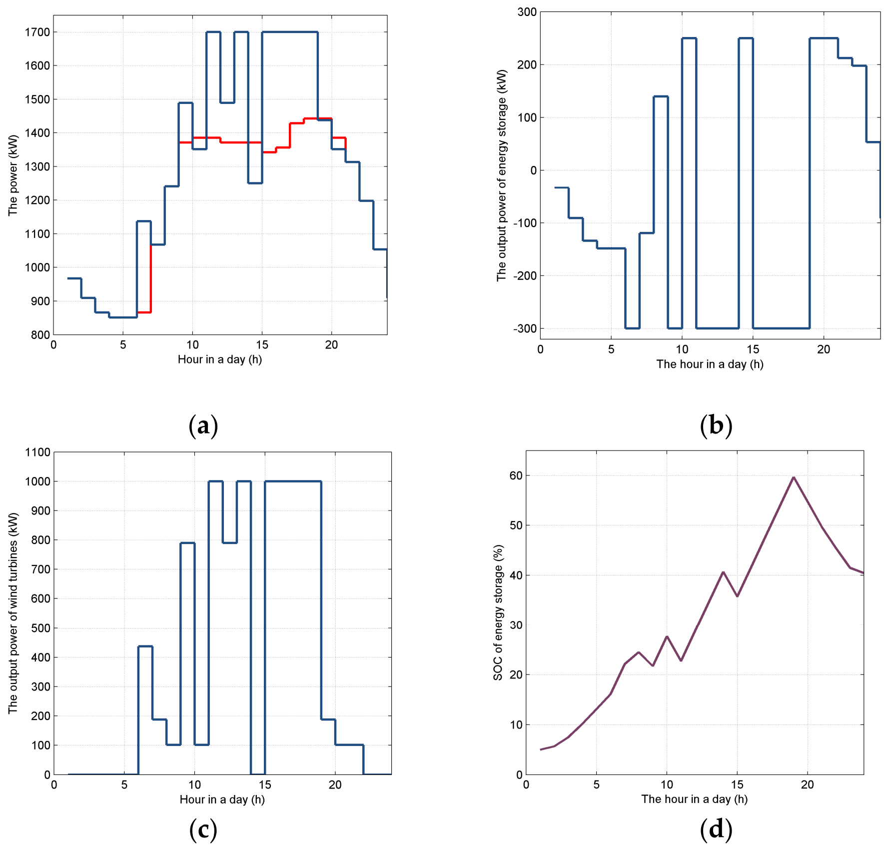

Figure 7. (**a**) The power flow of test system; (**b**) output power of energy storage; (**c**) output power of wind turbines; and (**d**) SOC of ESS.

The SOC and the wind power during the 24-h system operation are shown in Figure 7c,d, respectively. SOC of energy storage is shown in Figure 7d for the algorithm. As a result, the value of SOC in this algorithm reaches about 60% in the daily operation. Therefore, if it can use the rest of the generated power for charging the ESS, the total generation cost will be minimized.

4.2. Sensitive Analysis

The factors that affect the reliability will also affect the CVES. These factors are discussed in this section. They include the load yearly peak load, maximum permissible energy stored for storage power, the installed capacity of the wind turbines, the wind speed time series, the temperature and the failure rate and repair rate of the energy storage. The parameters of the test system are shown in Table 3. A sensitivity analysis of these factors is investigated in the following case studies.

Table 3. The main parameters of the test system.

Wind Turbines Parameters	
Rated power (P_r)	18,000 kW
Cut-in wind speed (C_{in})	3.75 m/s
Rated wind speed (C_{rate})	12 m/s
Cut-out wind speed (C_{out})	23 m/s
C_1	0.1203
C_2	−0.08
C_3	0.0128
Energy Storage System Parameters	
Maximum charging power (P_{EScha_Max})	800 kW
Maximum discharge power ($P_{ESdischa\_Max}$)	250 kW
Sampling time period (T)	1 h
Lower limit energy stored (E_{min})	500 kWh
Upper limit energy stored (E_{max})	10,000 kWh

4.2.1. Impact of the Load

In this study, the impact of the load yearly peak value on the CVES is analyzed. Figure 8 demonstrates the trends of the CVES with different load yearly peak powers. The values of the storage from the capacity value when the yearly peak power increases from 1800 kW to 3200 kW with a 200 kW step are shown in Figure 8. When the yearly peak load is low, the wind power is adequate to satisfy the load demand to maintain a certain reliability level. Thus, the energy storage system contributes little to the generation adequacy, and the value of storage from the capacity value is low. Therefore, from Figure 8, when the yearly peak load is lower than 1900 kW, the value of storage from the capacity value is 2 kW. Then, the storage values from the capacity value significantly increase when the load yearly peak power increases to 2400 kW. This is because the wind power cannot satisfy the load demand that keeps increasing, and the energy storage devices afford the rest of the load demand. Therefore, the storage values from the capacity value have a high growth rate. If the load yearly peak power keeps on increasing to 3200 kW, the energy storage system cannot supply the load demand any longer, and the growth rate of the CVES will slow down. Then, the energy storage from the capacity values will finally reach a steady level.

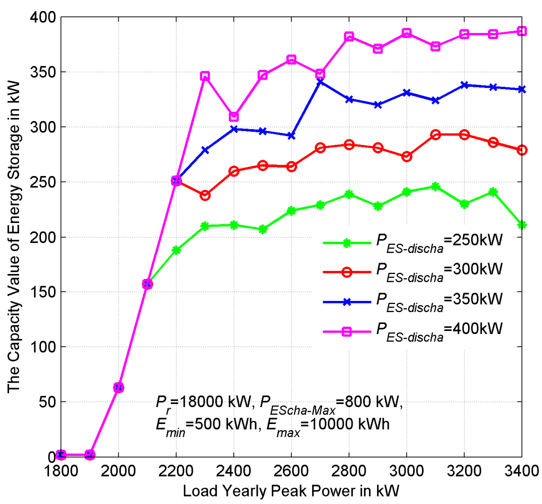

Figure 8. Variations of the CVES against the load yearly peak power.

With different maximum discharge powers, $P_{ESdischa\_Max}$, the CVES values have the same trends. When the load yearly peak power is low, the CVES values remain constant with varying $P_{ESdischa\_Max}$. In addition, if the peak load continues to increase, the CVES values with different $P_{ESdischa\_Max}$ will reach steady values.

4.2.2. Impact of the Wind Power

(1) Impact of the installed wind power capacity of the wind turbines

The trends of CVES are represented by the changes in the renewable energy penetration rate with different discharge output powers of the energy storage system, as shown in Figure 9.

The curves with different discharge output powers of the energy storage system have the same shape. When the rated output power of the wind turbines is low, the discharge power of the energy storage system has little influence on CVES values. Therefore, the contribution of the added energy storage with different discharge powers to the generation adequacy is the same. Then, with an increase in the rated output power of the wind turbines, the CVES values will increase to a stable value, and the energy storage with a higher discharge power has a larger CVES.

Figure 9 shows that when the rated output power of the installed wind turbines increases from 1800 kW to 2700 kW, the CVES values will rapidly increase. The energy stored in the energy storage system has been fully utilized, and no more stored energy is in excess of the load demand, which will be satisfied by the increased wind power. Therefore, when the rated output power of the installed wind turbines keeps increasing to 3600 kW, the CVES reaches a maximum value. Then, with the sustainable growth of the rated output power of the wind turbines, the CVES values rapidly decreases.

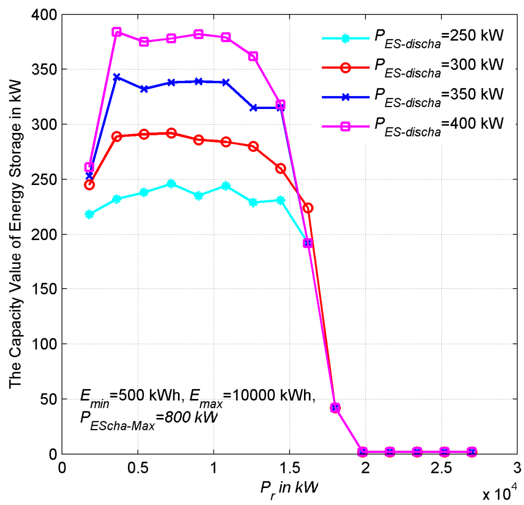

Figure 9. Variations of the CVES values against the different rated output powers of the wind turbines.

(2) Impact of the wind speed time series

Figure 10 demonstrates the CVES at the same location in Canada for different years. The comparison results are shown in Figure 10. In this study, the wind speed time series at Prince Alert, Canada in 2006 and 2012 are applied. Therefore, the influence of the wind speed time series is studied. From Figure 10, the changing trend of the capacity value of energy storage against the E_{max} of energy storage is the same. With the increasing of the E_{max} of energy storage, the system reliability increases. When the E_{max} of energy storage is determined, the capacity value of energy storage at different years is similar. Because the same location had similar climate conditions for different years, the CVES values have the same trends with respect to different E_{max} values for those two years.

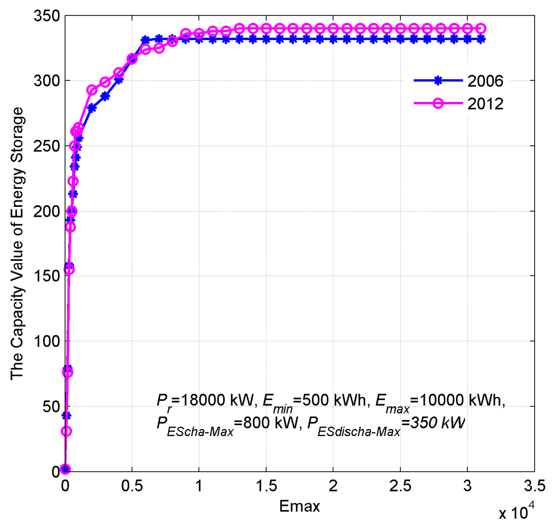

Figure 10. Variations of the CVES values against different E_{max} values with different wind speed time series.

However, as shown in Figure 10, the capacity value of energy storage in 2012 is higher than the capacity value of energy storage in 2012. Because the fluctuation of wind turbine output in 2012 is higher than the fluctuation in 2006.

4.2.3. Impact of the energy storage

(1) Impact of the maximum energy stored in the energy storage system

In this test, the maximum energy stored in energy storage system, E_{max}, is set from 0 kW to 4000 kW. Figure 11 shows the trends of the CVES values with different E_{max} values. In Figure 11, with the increase of E_{max}, there are three stages for the trends of the CVES.

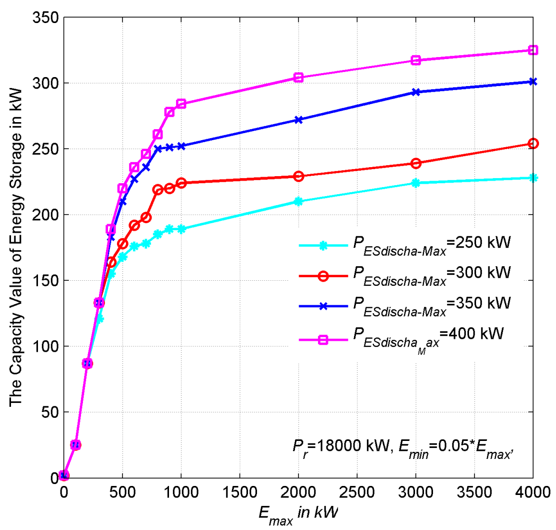

Figure 11. Variations of CVES against different E_{max} values of energy storage.

In the first stage, because of the intermittent characteristics of wind power, the wind turbines cannot commendably satisfy the load demand without energy storage. Therefore, after the energy storage devices are added, the system reliability is effectively improved, and the CVES rapidly increases during this stage. Then, as the load demand supplied by the energy storage system is restricted by the output of the wind power and conventional generators, the growth rate of CVES decreases. During this stage, the ability of the energy storage system to improve the power supply adequacy is limited. Therefore, with the increase in E_{max}, the CVES increases slowly in the second stage until it reaches a stable value. In the third stage, restricted by the operation mode of the energy storage devices, the CVES maintains a constant value.

With different maximum discharge powers, $P_{ESdischa\_Max}$, the CVES values have the same trends, and finally, they reach their stable values. In addition, the energy storage system with a higher discharge output power will have a higher CVES with the same E_{max}.

(2) Impact of the temperature

The systems under 25 °C and 0 °C are discussed in this section. Figure 12 shows the CVES values for the same location in Canada at different temperatures. The values of energy storage from the capacity values have the same shape with respect to different temperatures with different load yearly peak powers. When the load yearly peak power is in the range of 2000 kW to 2200 kW, the CVES values at different temperatures exhibit no significant changes. This is because energy storage is not used to the fullest when the load power is low. Therefore, the change in the capacity of a battery has little influence on the values of energy storage from the capacity values. In addition, when the load yearly peak power increases, the energy storage is put into full application. When the capacity of the energy storage system at 0 °C from the capacity value is reduced to 75% of the rated value, the energy storage capacity value below 0 °C is lower than that at 25 °C.

The steady value region yet shows some CVES oscillation with respect load yearly peak power, that because the capacity value of energy storage system is an integer programming. The relationship between energy storage capacity and peak load is not simple monotone increasing.

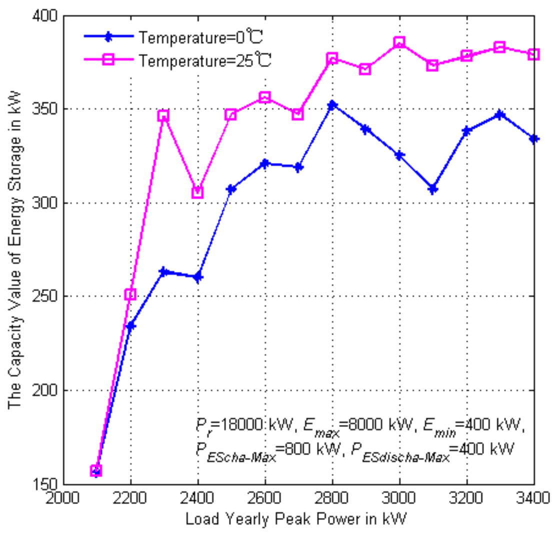

Figure 12. Variations of the CVES values against load yearly peak powers with different temperatures.

(3) Impact of the failure rate of the energy storage system

A comparison is provided for the CVES values between considering the failure rate and repair rate and not considering them, as shown in Figure 13. The failure rate of the grid-connected energy storage system is λ_{bat} = 0.307, and the repair rate is μ_{bat} = 20. With an increase in the load yearly peak power, the values of energy storage from the capacity value have the same shape. When the load yearly peak power is in the range of 1800 kW to 2000 kW, the CVES values considering the failure rate and repair rate of the energy storage system are the same as those without such considerations. Because the peak load is low, the energy storage system is not used to the fullest. In addition, the grid-connected energy storage system has a lower failure rate and repair rate. Therefore, the fault occurrences have minimal effects on the CVES values. When the load yearly peak power continues to increase, the energy storage utilization increases, and occurrence of the faults affect the CVES values. Considering the failure rate and repair rate, the energy storage system has a lower value of energy storage from the capacity value. This is because the potential reliability risk increases with the increasing of failure rate of energy storage system. As the peak load shifting of energy storage, system reliability will be effectively improved by the energy storage capacity value increasing, and the increasing of the installed capacity value of energy storage will compensate for the potential reliability risk of distribution network.

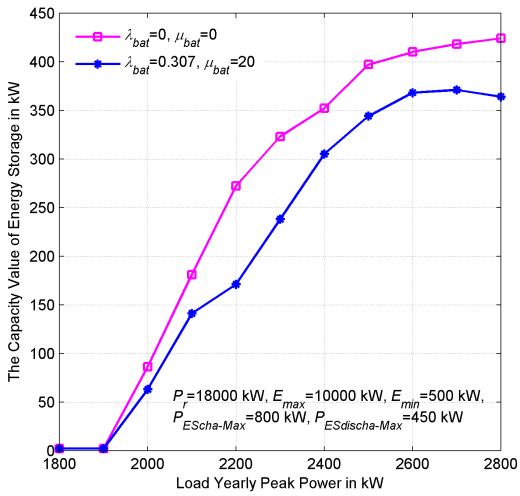

Figure 13. Effect of different failure rates in the energy storage system on the CVES values.

5. Conclusions

In this paper, the definition of the CVES is presented to quantitatively weigh the contribution of the energy storage to the generation adequacy. For this purpose, a method in accordance with EFC approach has been introduced to calculate the energy storage values from the capacity value. The developed model can also be used as a useful tool for the CVES value estimation to save the cost allocated to energy storage. Moreover, it can be used by planners to allocate the energy storage capacity. The approach is validated experimentally on a test system. The obtained results have demonstrated the effectiveness of the proposed algorithm in the CVES value estimating. The simulation results have shown that CVES effectively presents the available capacity of energy storage, and estimate the capacity contribution of ESS precisely. Furthermore, the impact factors on the CVES are investigated in the case study, such as the load yearly peak power, the maximum permissible energy stored in the system, the renewable energy penetration, the temperature, the failure rate and repair rate of the grid-connected energy storage system and the wind speed time series. The impact factors influence the supply-demand relationship of the actual energy storage output. The sensitivity analysis of the impact factors for the CVES is conducted. Therefore, the contributions and aims of the presented paper can be summarized as follows.

(1) Presenting the CVES to quantitatively weigh the contribution of EES to the generation adequacy.
(2) The CVES provides a feasible solution to quantitatively weigh the contributions of energy storage. In addition, it is related to the system load demand, the output power of wind turbines and the characteristics of energy storage devices.
(3) The peak load and the rated power of the wind turbines are comprehensively considered for the energy storage capacity optimization allocation. If the supply power is adequate, energy storage system is not used to the fullest. Therefore, the CVES value is low. In addition, when the

energy storage is sufficiently utilized, the CVES value reaches a maximum. There is no point in continuing to increase the energy storage capacity. Therefore, using the CVES, we can obtain a suitable energy storage capacity allocation scheme.

(4) When the energy storage devices are integrated to the grid, the system reliability is effectively improved, and the CVES values rapidly increases during this stage. Then, with the increase in E_{max}, the CVES increases until reaching a stable value. In addition, the E_{max} increases as well, but the contribution of the energy storage to the grid reliability did not increase. Therefore, the CVES values remain constant.

(5) The failure rate and repair rate of the energy storage and temperature affects the CVES. With the same parameters, if the energy storage system is not used fully, the influence of the temperature and failure rate of energy storage on the CVES is not apparent. However, if the energy storage system is more fully used, the CVES decreases if the ambient temperature and the failure rate and repair rate are considered.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

The following abbreviations are used in this manuscript:

Capacity Value Estimate Parameters and Variables:	
P_{wind_total}	Total output power of the wind turbines (kW)
P_{ES}	Output power of the energy storage system (kW)
HLOLE	Hourly loss of load expectation
G_i	Available capacity at hour i (kW)
L_i	Actual load level at hour i (kW)
P_L	Load power (kW)
n	Total number of hours in a year
Wind Power Model Parameters:	
v	Wind speed (m/s)
P_r	Rated output power of wind turbines (kW)
C_{in}	Parameter related to the cut-in wind speed of wind turbines
C_{rate}	Parameter related to the rated wind speed of wind turbines
C_{out}	Parameter related to the cut-out wind speed of wind turbines
C_1, C_2, C_3	Parameters related to the wind turbines
P_{Wind}	Output power of a wind turbine (kW)
Energy Storage Model Parameters:	
SOC	State of charge
P_{ES_output}	Power of the energy storage system (kW)
P_{status_cha}	Charging power of the energy storage system (kW)
P_{status_discha}	Discharging power of the energy storage system (kW)
E_{bat}	Energy stored in the energy storage system (kWh)
$P_{Available}(h)$	Available power of the energy storage system at hour h (kW)
P_{EScha_Max}	Maximum charging power of the energy storage system (kW)
$P_{ESdischa\_Max}$	Maximum discharge power of the energy storage system (kW)
$E_{output}(h)$	Output energy of the energy storage system at hour h (kWh)
T	Sampling time period (h)
E_{min}	Lower limit energy stored in the energy storage system (kWh)
E_{max}	Upper limit energy stored in the energy storage system (kWh)

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