Mode for reducing wind curtailment based on battery transportation

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Abstract Renewable energy sources, such as wind and solar, face several obstacles, including curtailment, where the generated energy exceeds local demand and production must be reduced because of limited transmission capacity. Simultaneously, consumer demand for large-capacity batteries is expanding given the recent rapid development of electric vehicles (EVs) and plug-in hybrid EVs. A battery-charging mode, in which discharged batteries are transported from battery exchange stations in high-load areas to wind farms, is proposed to alleviate curtailment. In this study, batteries store otherwise curtailed energy and smooth the wind power output simultaneously. The structure of the battery-charging device is discussed, and the

concept of a battery-charging container is proposed. The control principle of the battery-charging management unit is presented with a simulation model constructed in the PSCAD/EMTDC environment. A case study is simulated, and the feasibility of the mode is analyzed considering the levelized cost and energy losses. Simulation results show that this mode is a feasible solution to alleviating wind curtailment and providing fresh impetus for developing EV battery exchanges.

Keywords Wind curtailment, Battery-charging container, Transportation, Power smoothing

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1 Introduction

Excessive fossil fuel consumption and carbon emissions are increasingly becoming serious issues worldwide. Thus, researchers are gradually focusing on clean and sustainable renewable energy [1]. However, areas with abundant renewable energy resources are dispersed in remote locations, where local energy consumption is low but long-distance transmission capacity is limited. These regions can encounter severe wind and solar power curtailment, whereby power generation exceeds demand, and production must be reduced [2, 3]. For example, wind power generation resources in China are mainly concentrated in the north, whereas the load center is on the southeast coast. The capacity of long-distance transmission lines cannot match the supply, thereby leading to serious wind curtailment. Moreover, the imbalance leading to the limited capacity of the transmission line is inadequate for supporting a substantial delivery of excess wind power because the growth rate of the installed capacity of wind power is far more than the construction speed of a

supporting transmission line in a power system. In 2014, the proportions of wind power curtailment in Jilin Province, Heilongjiang Province, and Inner Mongolia are over 20%, thus indicating a rising trend [3]. This kind of transmission cannot maximize the use of wind energy, although electrical power transmission through power lines is known to most efficiently supply energy. Wind curtailment wastes many resources, affects the overall development of wind power, and limits the further penetration of renewable energy.

Reference [4] proposed an optimization using the peak-shaving capability of pumped storage to improve wind power consumption and address the wind curtailment problem. In Germany, Ref. [5] recommended that the Swiss pumped-hydro storage plants can be potentially used to reduce shortages and surpluses of renewable energy. Reference [6] proposed that the level of wind curtailment depends on the flexibility of the system; this flexibility depends on the proportions of the power generation units, combined cycle plants, and pumped hydro plants within the system. Reference [7] showed that power system operators can reduce the minimum power output of combined heat and power (CHP) to allow excess wind power to be utilized when integrating wind power and CHP units by introducing electrical boilers and heat storage tanks during the heating season. These techniques can slightly alleviate wind curtailment, but each technique has drawbacks, such as further difficult site selection given region- and terrain-related restrictions. Extended construction time and poor economic performance are critical issues, although increasing the transmission line capacity can solve wind curtailment [8]. Therefore, further flexible solutions to wind curtailment should be explored. These should require relatively brief planning and construction periods.

Consumer demand for large capacity batteries is dramatically increasing given the expansion of the electric vehicle (EV) and plug-in hybrid EV industries, thereby driving development and competition in the battery industry. Battery performance, such as specific capacity, continues to improve, whereas the price per kilowatt rapidly decreases. However, large-scale unplanned charging of EVs and plug-in hybrid EVs may cause a large and intermittent load on the existing power grid. This unpredictable load can seriously affect power grid stability [9, 10]. Reference [11] proposed to effectively handle the prediction of wind power error using the energy storage battery, which built a “source-grid coordination” method using energy storage devices to reduce both wind power dispatching risk and wind curtailment; these researchers also evaluated the feasibility of improving acceptable wind power system scale for the proposed scheme in different probability intervals. However, this method is only used for the wind curtailment phenomenon caused by wind speed

forecast error, and is not applicable to the situation caused by insufficient capacity of the transmission line. A method, in which EV accepts global operational regulation of the power grid, is proposed to cooperate with renewable energy power generation on the basis of vehicle-to-grid. However, this method currently requires a highly intelligent power grid [12–14].

Given the limited capacity of transmission lines and current situation of wind curtailment, this paper proposes a new battery-charging mode to solve problems on the power-generation and consumer sides simultaneously. The new battery-charging mode aims to transport discharged batteries from battery exchange stations to wind farms and charge batteries using energy that would otherwise be curtailed. These batteries can be used to smooth the power output and improve supply quality. In a normal battery-charging process, a stable power supply is required. However, the output from a wind turbine generator (WTG) fluctuates. Therefore, corresponding simulation and analysis are required.

The remainder of this paper is organized as follows. Section 2 describes the proposed mode and discusses the charging structure. Section 3 presents the simulation and relevant control principles. A lithium-ion battery currently on the market is modeled. The simulation model, based on a first-order low-pass filter and P - Q decoupling control, is established in the PSCAD/EMTDC environment. Section 4 demonstrates the case study and related analysis. Section 5 explains the economic feasibility of the mode. Section 6 gives the conclusions of the paper.

2 Mode description and battery-charging structure

2.1 Mode description

The present study uses a wind farm, where wind curtailment occurs as an example shown in Fig. 1. The discharged batteries from battery exchange stations in the load center area can be transported to the wind farm and charged centrally by installing battery-charging devices at the wind farm and using rail or other low-cost transportation. These batteries store surplus energy and smooth unstable wind power output simultaneously. Whereas the batteries are fixed in typical existing battery energy storage systems (BESSs), the battery modules (BM)s in this mode can be detached from the charging facilities and transported to the load center for the use of EV once fully charged.

Various complicated reasons lead to curtailment. Different curtailment commands and wind regimes may result in difficulty in forecasting the required battery quantity. However, a single WTG or wind farm rarely transmits

Fig. 1 Structural description of mode

power over a long distance. Generally, powers from multiple sources are centralized and jointly outputted. This clustering can reduce fluctuations in wind power output by increasing the scale of the center, thereby generating a predictable forecast of curtailment ratio. Consequently, accurate wind-speed predictions and a reasonable scheduling plan can install charging facilities in such a center, and the required number of batteries can be determined within a rational range.

2.2 Logistics design based on mode

The mode involves the transport and dispatch of batteries; this activity is the network structure between multiple power fields and users. The dispatch plan of the batteries is mainly developed with the battery distribution points of the respective load center areas by outlining the forecast information of the power generation and EV user sides combined with the actual situation. Thus, the operator can optimize the dispatch process of batteries at the system level to ensure that another batch of empty batteries is transported to the wind farm when the charging batteries are nearly full. The logistics process based on the mode is illustrated in Fig. 2.

2.3 Battery-charging structure

Currently, two main typical methods exist to incorporate the BESS into a WTG power system. The first method is connecting the DC link between the continuous pulse-width modulation (PWM) inverters of the WTG via a DC/DC converter. The second method is directly connecting the grid through the DC/AC or DC/DC + DC/AC inverters. Capacity expansion and modular management are easily achieved through the second method [15], thereby verifying the suitability of the proposed mode.

The battery-charging system for this novel mode shown in Fig. 3 comprises transportable BMs, switches, battery

management system (BMS), power conversion system (PCS), WTG, and the grid. Multiple BESS subsystems are connected in parallel with a unified BMS. The target power output of BESS can be calculated by the BMS according to the specific wind curtailment, acceptable fluctuation range of wind power, and state of charge (SOC) of the battery by measuring the power output of the WTG. The PCS comprises a three-phase voltage source inverter and LCL low-pass filter circuit. The PCS is directed by the BMS and controls the magnitude and direction of the power. Each subsystem in the BESS comprises numerous detachable BMs connected in series; each BM consists of individual batteries connected in series-parallel. The battery-charging system is realized when the BESS subsystems are connected in parallel to the DC link of the PCS through a DC/AC inverter and LCL filter circuit, thereby providing an AC supply that can be connected. The BESS controlled by the BMS stores the oversupplied energy and smoothes the WTG power output.

2.4 Battery-charging container

The BMs in this mode can be of a variety of types given the diverse battery manufacturers compared with the typical BESS with a uniform battery type. The BESS increases the difficulty in managing battery-charging and complexity of the charging structure. The present paper proposes the battery-charging container (BCC) to address the above-mentioned problem. The BCC can be considered the charging interface available for BMs to be plugged in and out. The general characteristic parameters of the BCC, such as size, range of voltage level, rated power, and energy capacity, must be standardized. The internal structure of the BCC can be differently designed by manufacturers according to specific battery types and characteristics. The discharged BMs in the battery exchange station can be directly plugged into the corresponding BCC after the off-line equalization processing (to control the SOC of BM at the same level). BMs are connected in series-parallel to satisfy the general characteristic parameters through the internal circuit of the BCC. The BCCs are uniformly transported to the wind farm by rail once fully filled with discharged BMs. The BCC can simplify the battery-charging management with different battery types. This is also convenient for transportation.

The general characteristic parameters of BCCs can be standardized and easily implemented. However, the charge-discharge and transient characteristics of BCCs may still differ from each other, thereby requiring the BCC to comprise different battery types. The change in open circuit voltage (U_{oc}) and impedance characteristic of each BCC can be different along with varying SOC. Therefore, a unified control via a single PCS module may result in an

Fig. 2 Logistics process based on mode

Fig. 3 Topology of battery-charging system

overlarge charging current and even overcharged BCCs. Consequently, independent PCS modules for BCCs of different battery types are necessary; thus, precise charging management can be implemented to extend battery life shown in Fig. 4a.

The BMS can use different control strategies consistent with a particular battery type and real-time state monitoring. The reference signal of the whole power output P_{ref} on the basis of specified monitoring results can be divided into several parts P_i ($i = 1, 2, \dots, n$, where n represents the number of battery types). The charging current for each BCC can be controlled within a suitable range, and overcharging can be avoided. The circulation path is blocked, and the circulating current is eliminated because the BCCs are separated from each other. Moreover, each inverter

(a) BESS topology considering different battery types

(b) BESS topology with DC/DC converter to improve voltage class

PCC: point of common coupling

Fig. 4 Charging structure

bears a relatively low power output to improve the reliability and energy efficiency of the entire system.

However, the DC output-voltage range of this topology is narrow, that is, the BCC cannot directly connect to a grid with low voltage class. In this case, installing DC/DC converters can increase the voltage class of the BCCs in Fig. 4b. This topology can realize the independent power control of each BCC. However, the total required power capacity of switching devices is considerably higher in this topology than in the topology presented in Fig. 4a. This increases the potential cost. Furthermore, using only one DC/AC inverter may be insufficient for the demand when the required power capacity is relatively large. Consequently, increasing the number of the DC/AC inverters in parallel to expanding supply capacity is necessary. Several appropriate measures suppressing the circulating current, such as using transformers for electric isolation or proportional–integral (PI) controller, must be adopted because parallel DC/AC inverters share a common DC link, providing a path for a zero-sequence circulating current [16, 17].

The simulation model is constructed according to the structure of Fig. 4a, and the SOC control method is designed. For SOC control, the difference among the BESS subsystems in the BM type is only in terms of capacity, available SOC range, and rated power. The flowchart of SOC control is demonstrated in Fig. 5.

Fig. 5 Flow chat of SOC control

The SOC control strategy can be flexible according to specific goals; however, this strategy requires an assurance that each power distribution will not cause power overrun or overcharge any subsystem. The basic power distribution method is as follows:

$$\begin{cases} P_{i_ref}^+ = P_{ref} \frac{\alpha_i^+ E_{i_rate} (SoC_i - SoC_{i_min})}{\sum_{j=1}^n [\alpha_j^+ E_{j_rate} (SoC_j - SoC_{j_min})]} & P_{ref} > 0 \\ P_{i_ref}^- = P_{ref} \frac{\alpha_i^- E_{i_rate} (SoC_{i_max} - SoC_i)}{\sum_{j=1}^n [\alpha_j^- E_{j_rate} (SoC_{j_max} - SoC_j)]} & P_{ref} < 0 \end{cases} \quad (1)$$

where $j = 1, 2, \dots, i, \dots, n$; $P_{i_ref}^+$ and $P_{i_ref}^-$ are the reference power that the i^{th} subsystem must emit or absorb; E_{i_rate} is the rated capacity of the i^{th} subsystem; SoC_i , SoC_{i_max} , and SoC_{i_min} are the current SOC, upper SOC limit, and lower SOC limit of the i^{th} subsystem, respectively; α_i^+ and α_i^- are the discharge and charge coefficients of the i^{th} subsystem, correspondingly, defaulting to 1. Each subsystem can be simultaneously filled when the initial values of SOC are unequal and α_i^+ and α_i^- of all subsystems are considered 1 through the feedback control of the SOC. The charging coefficient of the part of subsystems can be increased, and the discharge coefficient can be reduced when partial subsystems must be preferentially filled according to the dispatch plan. Power distribution must be conducted on the basis of the initial values of SOC according to (1). Power must only be redistributed without SOC feedback control after the corresponding subsystem is full.

The battery-charging structure in this mode can be modified according to the specified situation and control objective. In practice, the charging structure must be comprehensively considered from technical and economic aspects.

3 Simulation model and control principle

3.1 Lithium-ion battery model

Lithium-ion batteries are used in EVs [18], power systems [19], and many other areas given the benefits, such as high efficiency, high energy density, low self-discharge rate, and long cycle life [20]. Therefore, this study considers lithium-ion battery the research object and establishes the corresponding first-order transient response model. The equivalent circuit is depicted in Fig. 6, where U_p is the battery polarization voltage; U_t is the battery terminal voltage; R_0 is the ohmic resistance; R_1 is the polarization resistance; C_1 is the polarization capacitance.

Fig. 6 Equivalent circuit of first-order transient response model

3.2 Control model and principle

Wind curtailment occurs when certain WTGs in a wind farm are required to reduce power output or cease operation, even under normal operating conditions. The reasons for curtailment are complicated, and specified curtailment commands are provided through automatic generation control in real time. To simplify, the wind curtailment index is assumed as K_c in this study.

$$K_c = \frac{P_a}{P_w} \quad (2)$$

where P_a is the maximum acceptable power during the period; P_w is the actual power output of the wind farm. When P_w is larger than P_a , the BMS controls the BESS to cover the difference between these systems instantaneously. This part of the BESS power output is denoted as P_{B_curt} .

$$P_{B_curt} = \begin{cases} P_a - P_w & P_w > P_a \\ 0 & P_w \leq P_a \end{cases} \quad (3)$$

$$P_s = \begin{cases} P_a & P_w > P_a \\ P_w & P_w \leq P_a \end{cases} \quad (4)$$

where P_s is the power output after subtracting the curtailed energy. Owing to wind instability, P_s fluctuates and negatively affects stable operation of the grid. Therefore, the BESS is used for simultaneous smoothing. In this study, a first-order low-pass filter is adopted to smooth the power output, thereby making the final power output P_f conform to the power quality standard of the grid [21]. Figure 7 illustrates the block diagram of the BESS power output. T

Fig. 7 Block diagram of BESS power output

is assumed as the time constant of the low-pass filter; then, P_f is expressed as:

$$P_f(s) = \frac{1}{1+sT} P_s(s) \quad (5)$$

whereas the smoothing part of the BESS power output is defined as:

$$P_{B_smooth}(s) = P_f(s) - P_s(s) = \frac{-sT}{1+sT} P_s(s) \quad (6)$$

The final power output reference P_{ref} can be obtained by adding P_{B_curt} and P_{B_smooth} :

$$P_{B_curt}(t) + P_{B_smooth}(t) = P_{ref}(t) \quad (7)$$

The energy storage system working in the grid-connected mode can usually be considered a P - Q node; thus, a simple and easy P - Q decoupling control strategy can be used [22]. The inner current-control and outer power-control loops are adopted in the present study. e_a , e_b , e_c , and i_a , i_b , i_c are the instantaneous values of voltage and current, respectively, of each phase. The active power P and reactive power Q can be expressed as:

$$\begin{cases} P = e_d i_d + e_q i_q \\ Q = e_d i_q - e_q i_d \end{cases} \quad (8)$$

where e_d , e_q and i_d , i_q are the components in the d and q axes, which are derived from the Park transform of e_a , e_b , e_c , and i_a , i_b , i_c , respectively. The q -axis is selected as the same direction as the voltage vector in the Park transform; the voltage component of the d -axis is 0; thus,

$$\begin{cases} P_{ref} = e_q i_{qref} \\ Q_{ref} = -e_q i_{dref} \end{cases} \quad (9)$$

In this study, P_{ref} is the reference active power, whereas Q_{ref} is the reference reactive power. The power deviation is controlled using a PI controller; the reference signals required for the inner current-control loop, i_{qref} and i_{dref} , are obtained. Accordingly, the final reference voltages of the inverter, v_{qref} and v_{dref} can also be derived.

$$\begin{cases} i_{qref} = -\left(K_p + \frac{K_i}{s}\right) (P_{ref} - P) \\ i_{dref} = -\left(K_p + \frac{K_i}{s}\right) (Q - Q_{ref}) \end{cases} \quad (10)$$

$$\begin{cases} v_{qref} = -\left(K_p + \frac{K_i}{s}\right) (i_{qref} - i_q) + e_q - \omega L i_d \\ v_{dref} = -\left(K_p + \frac{K_i}{s}\right) (i_{dref} - i_d) + \omega L i_q \end{cases} \quad (11)$$

where L is the inductance of the filter between the inverter and the grid; K_p and K_i are the proportional-integral coefficients of the PI controller.

The overall block diagram is presented in Fig. 8. A signal error occurs when the actual power output is unequal

Fig. 8 Block diagram of P - Q control

to the reference power. The adjustment of the PI controller eventually reduces the error to zero. In this study, the BESS is assumed to be operating with unity power factor to achieve the 0 value of Q_{ref} .

4 Case study and analysis

In this study, the system and its main components, including the WTG, lithium-ion battery, and PCS module, are modeled in the PSCAD/EMTDC environment according to the structure demonstrated in Fig. 3. The simulation parameters include the line voltage of the output terminal of WTG, 480 V (RMS); voltage of the DC link of the inverter, 800 V; grid line voltage, 35 kV (RMS); and grid frequency, 60 Hz. The simulation parameters of the WTG and lithium-ion battery are listed in Table 1.

4.1 BESS power output considering curtailment and smoothing

To simplify, a 24-hour scheduling period serves as an example, with a constant wind curtailment level. The curtailment index K_c is assumed as 0.6. The fluctuation limit of active power is satisfied with a cutoff frequency of

0.0007 Hz. The wind speed and power output of each part at the cutoff frequency are depicted in Fig. 9. The sampling interval of wind speed is 1 min. Given that the rated power of WTG is 2.5 MW and curtailment index K_c is 0.6, the upper limit of power output is 1.5 MW. P_s is derived from P_w by subtracting the curtailed energy, and P_f is the final power output delivered to the grid after smoothing. The fluctuation of P_f is lower than the set value of 1/10 rated power per 1 min (0.25 MW/min) and 1/3 rated power per 10 min (0.83 MW/10 min), thereby conforming to the corresponding requirement of power quality. P_{B_curt} is the portion of the BESS power output that stores the curtailed energy. Negative values indicate that the part draws and stores power. The power P_{B_smooth} represents the smoothing portion of the BESS power output. The final power output P_{ref} of the BESS is obtained as the sum of P_{B_curt} and P_{B_smooth} .

The calculation results are summarized in Table 2. In this case, the battery capacity used to store the curtailed energy is sufficient for power smoothing. Overall, the required BESS energy capacity is 2.9359 MWh, and the required power is 1.1626 MW. The lithium-ion battery presented in Table 1 is considered as an example. A total of 190 batteries must be connected in series to form each BESS subsystem, and 180 BESS subsystems should be connected in parallel to satisfy the energy capacity and DC bus voltage class. In reality, battery packs from EVs and plug-in hybrid EVs possess considerably higher powers and larger capacities than the batteries selected in this study. Therefore, each battery pack considered a BM will significantly reduce the required number of BMs in series and the number of BESS subsystems in parallel.

4.2 Simulation of battery-charging process

All the batteries or BMs are well made with consistent performance; the total BESS simulation model can be obtained by using a simple series-parallel equivalence. The initial SOC of the BESS is assumed to be 0.1. In Fig. 10, there are minimal intermittent declines in the SOC but with

Table 1 Simulation parameters of wind turbine generator and lithium-ion battery

Wind turbine parameter	Value	Lithium-ion battery parameter	Value
Rated power (MW)	2.5	Rated capacity (Ah)	25
Cut-in speed (m/s)	4	Rated voltage (V)	3.6
Cut-out speed (m/s)	25	End-of-charge voltage (V)	4.2
Rated speed (m/s)	12	End-of-discharge voltage (V)	3.4
Blade radius (m)	52.8	Maximum charging current (C)	1
Utilization ratio of wind power	0.27	Maximum discharging current (C)	3

Fig. 9 Wind speed and power output during 24 hours

Table 2 Simulation results

Parameter	Value
Total output energy (MWh)	22.3687
Curtailed energy (MWh)	2.9359
Curtailment ratio (%)	13.12
Capacity in need for smoothing (MWh)	0.0712
P_{B_smooth} (MW)	0.7653
P_{B_curt} (MW)	1
P_{ref} (MW)	1.1626

a steady upward trend eventually reach approximately 0.9 because of smoothing. U_{oc} gradually approaches the end-of-charge voltage along with the change in SOC. The probability distribution curve according to the current magnitude (C rate) is plotted in Fig. 11. The value is mainly distributed between -0.2 C and 0.1 C, and the maximum absolute value is 0.323 C, which is within the maximum acceptable magnitude of 1 C. Thus, excess current will not adversely affect the lifespan of the battery. Consequently, the power of the BESS is also sufficient in this mode when the BESS satisfies the energy capacity.

Fig. 10 Variation of SOC, U_{oc} and current of BESS during 24-hour charging process

The polarization effect during the battery-charging process leads to accumulated ions near the electrodes and may hinder the charging process by reducing the maximum

Fig. 11 Probability distribution and normal distribution curve of current magnitude

acceptable magnitude of the charging current. The intermittent discharge behavior of smoothing, which is similar to the role of negative pulses in the pulse-charging process [23], can alleviate the battery polarization effect and improve the battery-charging process.

The case study simulation and results above indicate that the BESS for storing curtailed energy can also smooth the WTG power output. The power of the BESS and premise of energy capacity are sufficient in meeting the demand.

5 Discussion on economic feasibility

5.1 Comparison between levelized cost of proposed mode and residential electricity price

The transmission cost of the proposed mode is calculated by using the levelized cost (in yuan/kWh, the same as the unit of electricity), which is compared with the residential electricity price in China and the United States based on the transmission and distribution mode (T&D mode), to analyze the future economic benefits of the mode.

5.1.1 Levelized cost of mode

The levelized cost of the mode Q expressed in (12) includes four aspects, namely, the levelized cost of infrastructure investment Q_1 , the levelized cost of buying the power of wind curtailment from a wind farm at a discounted price Q_2 , the levelized cost of battery transportation Q_3 , and the environmental benefits of promoting renewable energy development and utilization by the mode T_e . T_e is set at 0.23 yuan/kWh according to [11].

$$Q = Q_1 + Q_2 + Q_3 - T_e \quad (12)$$

The following calculates each cost separately.

1) The levelized cost of infrastructure investment Q_1 is expressed as:

$$Q_1 = \frac{Q_{char} + Q_{line}}{En_{year}} \quad (13)$$

where the infrastructure investment costs mainly include Q_{char} , the battery-charging device and installation fee, and Q_{line} , the construction fee for short-distance medium or low voltage transmission lines used to connect wind farms and battery-charging stations. E is the average annual charge capacity of the battery using the wind, and n_{year} is the operating life of the infrastructure. Q_{char} 's calculation formula is:

$$Q_{char} = c_{char}P_{char} \quad (14)$$

where c_{char} is the unit price (yuan/kW) of the charging device cost and installation fee; P_{char} is the rated power (kW) of the battery-charging device. This can be approximated by multiplying the regional total rated power of wind power P_{wind} by the region's average annual wind curtailment ratio r_{curt} , as shown in (15).

$$P_{char} = P_{wind}r_{curt} \quad (15)$$

Q_{line} 's calculation formula is:

$$Q_{line} = c_{line}l_{line} \quad (16)$$

where c_{line} is the cost per kilometer (yuan/km) of medium or low voltage transmission line; l_{line} is the length (km) of transmission line. E can be calculated by (16), where n_{hour} is the average annual operating hours of the wind farm.

$$E = P_{wind}n_{hour}r_{curt} \quad (17)$$

The final calculation of Q_1 is as follows:

$$Q_1 = \frac{c_{char}P_{wind}r_{curt} + c_{line}l_{line}}{P_{wind}n_{hour}r_{curt}n_{year}} \quad (18)$$

In this paper, there are some assumptions: that the total rated power of wind power in a region is 5000 MW, the average annual operating hours are 2000 [24], and the average annual wind curtailment ratio is 20%. The operational life of the infrastructure is assumed to be 25 years. Short-distance transmission lines between wind farms and battery-charging stations have a voltage rating of 110 kV. To simplify the calculation, the cost per kilometer is set at 1 million yuan/km and the total length is 80 km [25]. c_{char} is taken as 1100 yuan/kW [26].

2) The levelized cost of buying the power of wind curtailment Q_2 is expressed as:

$$Q_2 = c_{wind}k_{dis} \quad (19)$$

where c_{wind} is the feed-in tariff of wind power (yuan/kWh) in that year; k_{dis} is the proportion coefficient of the wind power purchased by the operators at a reduced price, which can be adjusted according to the actual

situation. This paper sets k_{dis} to 0.4 to simplify the calculation. Based on the forecast of feed-in tariff of wind power in China [27–29], the forecast curve is shown in Fig. 12.

3) Assuming that 20-foot containers are used for battery transportation, the transport cost of a single container is linearly related to the transport distance, as shown in (20).

$$Q_{container} = aL + b \quad (20)$$

where $Q_{container}$ is a single-pass cost (yuan) for transporting a battery-filled container from charging station to exchange station; L is the transport distance (km). According to the related container parameter [30], a and b are set at 2.025 and 500 respectively. Thus, the levelized cost of battery transportation Q_3 for round-trip transportation can be expressed as:

$$Q_3 = \frac{2Q_{container}}{d_{BM}M_{BM} \times 1000} \quad (21)$$

where d_{BM} is the equivalent energy density of BM (kWh/kg); M_{BM} is the weight of the BM transported in a single container (28.48 ton), which is obtained by subtracting the dead weight (2 ton) from the total weight M_{total} (30.48 ton) for a container. Taking the Tesla 85 kWh BM as an example, the trend of equivalent energy density of BM is as shown in Fig. 13 based on available data [31] and predicted trends of battery energy densities [32, 33].

5.1.2 Residential electricity price and trend forecast

The residential electricity price for recent years in the U.S. is shown in Table 3.

Fitting the data in Table 3 shows that the average residential electricity price in U.S. increases linearly with the year generally. Thus it is possible to make an approximate prediction of the future price of residential electricity price in the U.S. The trend of residential electricity price in China is still unpredictable after the completion of the power market reform. However, in the long run, since electricity price mainly depends on energy price, the rising trend of residential electricity price in China is

Fig. 12 Feed-in tariff of wind power in China

inevitable after a gradual replacement of coal-fired power with non-fossil fuels. This paper assumes that the future trend of China's residential electricity price on the basis of the current (about 0.6 yuan/kWh) is similar to that of the U.S., to make a forecast for China. The exchange rate of USD and RMB is taken as 1: 6.76.

5.1.3 Comparison

The comparison according to the reasonable calculation between the levelized cost of the mode and residential electricity price in China and the United States is presented in Fig. 14. The levelized cost of the mode at the current level of battery technology and electricity prices (2015) will be lower than the residential electricity price in China when the transport distance is less than 500 km. The mode is economically feasible at this time. The residential electricity price is higher in the United States than in China, and thus the limit of the battery transport distance increases to 800 km under the corresponding conditions. The levelized cost of the mode based on the prediction about the increase rate of the equivalent energy density of the BM (the speed of current research and development) will eventually decline significantly. Meanwhile, the limit of the battery transport distance combined with the upward trend in electricity prices will constantly increase. This will likely offer improved economic benefits and further enhance its economic viability in the future.

5.2 Comparison of energy losses between proposed mode and T&D mode

5.2.1 Energy losses of T&D mode

The transmission losses of the traditional T&D mode [34–38] can be divided into the following three parts.

- 1) Short-distance transmission line losses between wind field and step-up transformer as well as step-up

Fig. 13 Improvement trend of BM's equivalent energy density

Table 3 Average residential electricity price in the U.S from 2005 to 2015

Year	Price (cent/kWh)
2005	9.45
2006	10.40
2007	10.65
2008	11.26
2009	11.51
2010	11.54
2011	11.72
2012	11.88
2013	12.13
2014	12.52
2015	12.65

Fig. 14 Comparison between the levelized cost of the mode and the residential electricity price in China and U.S. according to different distances (based on forecast)

transformer losses x_1 , whose typical value is between 1% and 3% of the total power transmission, taken as 2% for the paper.

- 2) Long-distance transmission line and step-down transformer losses x_2 , which are approximately 1.57%, 2.66%, 4.09%, 5.76% and 7.43% for the transmission distances of 500, 1000, 1600, 2300 and 3000 km, assuming that the transmission line voltage is 1000 kV.
- 3) Distribution line and distribution transformer losses x_3 , whose typical value is between 5% and 15% of the total power transmission, taking 8% for this paper.

The energy losses of the T&D mode over the entire transmission process x_{loss} can be calculated as:

Fig. 15 Comparison of energy losses between the proposed mode and the T&D mode according to different distances and the BM's equivalent energy density

$$x_{loss} = [1 - (1 - x_1)(1 - x_2)(1 - x_3)] \times 100\% \quad (22)$$

If wind curtailment is considered as an indirect loss of energy in the T&D mode, the final loss can be calculated by (23), where r_{curt} is the wind curtailment ratio with the adoption of 20% here.

$$x'_{loss} = [1 - (1 - x_{loss})(1 - r_{curt})] \times 100\% \quad (23)$$

5.2.2 Transmission losses of proposed mode

The transmission losses of the proposed mode can be divided into two parts.

- 1) Short-distance transmission line losses between wind curtailment farms and the battery-charging stations y_1 , which is close to x_1 in the T&D mode, again taken as 2%.
- 2) Energy losses of the battery transportation y_2 is expressed as:

$$y_2 = 2 \frac{gM_{total}L}{d_{BM}M_{BM} \times 1000} \quad (24)$$

The numerator of (24) is the energy consumed to transport a single container at a transport distance of L , the denominator is the total energy of the batteries transported in the container, and the factor of 2 is due to round-trip transportation.

In (24), g is the energy consumption per ton per kilometer of goods transported by freight train (kWh/(ton·km)), and 0.01048 kWh/(ton·km) is taken in this paper [39]. Also based on the relevant parameters for 20-foot container, d_{BM} , M_{BM} , M_{total} are the same as before. The energy losses y_{loss} of the proposed mode for transmission can be calculated as:

$$y_{loss} = \left[1 - (1 - y_1) \left(1 - 2 \times \frac{gM_{total}L}{d_{BM}M_{BM} \times 1000} \right) \right] \times 100\% \quad (25)$$

5.2.3 Comparison

Based on predicting the equivalent energy density of the BM, the comparison of energy losses between the proposed and T&D modes under different distances is illustrated in Fig. 15. For the T&D model, x_{loss} and x'_{loss} are both calculated, which are labeled separately. The dots in Fig. 15 represent T&D mode without considering wind curtailment which the triangles represent T&D mode considering wind curtailment. As can be seen, energy losses of both modes decrease rapidly as the BM's equivalent energy density increases.

The proposed mode becomes competitive in terms of transmission efficiency when wind curtailment is considered as an indirect energy loss in the T&D mode. The transmission energy loss is lower in the proposed mode than in the T&D mode up to the farthest distance of 3000 km, even in current conditions of the equivalent energy density of the BM. According to the forecast, the equivalent energy density of the BM will exceed 0.21 kWh/kg in 2025, and the transmission efficiency will be better in the proposed mode than in the traditional T&D mode, even at 3000 km. The transmission efficiency of the proposed mode has a large advantage with the increase in the equivalent energy density of the BM, and this is feasible in the future.

An EV charged through the power grid will rely on traditional fossil-fuel power plants as the major energy source. This condition simply relocates the pollution caused by city cars to the pollution caused by the fossil-fuel power plants in the rural area. The carbon emissions of EVs after the conversion may exceed the emissions by traditional gasoline vehicles in the country, which is dominated by thermal power [40]. Comparatively, the power for EV in the proposed mode will come from renewable power plants, which can significantly reduce the amount of carbon emissions.

If realized, then the proposed mode can solve the wind curtailment problem and substantially increase the penetration rate of wind power. Otherwise, capturing and using curtailed energy will increase the cost-effectiveness of wind farms. The proposed mode may obtain additional returns through the carbon-trade market, thus enabling wind power to better compete with other forms of power generation in the electricity market. For consumers, this mode can encourage the deployment of battery exchanges, which reduce charging time and improve efficiency. This mode is applicable to any renewable power plant experiencing oversupply and subsequent curtailment.

6 Conclusion

This study proposes that wind farms use large quantities of discharged batteries to store energy that will otherwise be curtailed. Batteries will be transported between wind farms and load centers via rail or other low-cost means. The battery-charging structure based on the new mode is introduced, and a case study is simulated. The results indicate the feasibility of the mode. The batteries used to store the curtailed energy can smooth the wind power output. The analysis of the levelized cost and energy losses proves the economic feasibility of the mode. In the proposed mode, the energy consumption will not significantly affect using renewable energy, especially because the energy used is curtailed. In future research, a new case study on aggregated wind power of different wind farms will be considered. This novel mode may improve the penetration of renewable energy. This study provides insights on promoting renewable energy in the future, although the proposal and the discussion are based on a simulation.

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