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A Storage and Transmission Joint Planning Method for Centralized Wind Power Transmission

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Abstract: Centralized delivery has become the main operation mode under the scaled development of wind power. Transmission channels are usually the guarantee of out-delivered wind power for large-scale wind base. The configuration of transmission capacity, which has the features of low utilization and poor economy, is hardly matching correctly due to the volatility and low energy density of wind. The usage of energy storage can mitigate wind power fluctuations and reduce the requirement of out-delivery transmission capacity, but facing the issue of energy storage cost recovery. Therefore, it is necessary to optimize the allocation of energy storage while considering the problem of wind power transmission. This paper studies the joint optimization of large-scale wind power transmission capacity and energy storage, reveals the mechanism of energy storage in order to reduce the power fluctuation of wind power base and slow down the demand of transmission. Then, analyze the multi-functional cost-sharing mode of energy storage, improve the efficiency of energy storage cost recovery. Constructs the coordination optimization configuration model to deal with the problem of large-scale wind power transmission capacity and energy storage, and realizes the transmission capacity optimization coordination and optimization with energy storage. The proposed method is verified by a wind base located in Northeast China.

1 Introduction

Wind power is developed vigorously in the last 10 years, which is a major measure of many countries to promote the transition to low-carbon energy and respond to climate change. The overall capacity of all wind turbines installed worldwide by the end of 2019 reached 65,100 MW, which is 5 times more than the capacity in 2009 according to statistics showed in [1]. Taking China as an example, 10 tens of millions of kilowatt wind power bases are successively built in many provinces, such as Gansu, Xinjiang, Hebei, Jilin, Jiangsu, and Shandong. The installed

wind power capacity is predicted to exceed 1.1 billion kW in 2030 and reach 2.4 billion kW in 2050 [2]. Wind power is developed on large scale based on wind energy distribution in China, and the centralized delivery of wind power is the main operating mode to transmit power to the substations outside the wind base.

The wind power base usually is far from the load center with small local power demand in the weak grid. Supporting power transmission projects are constructed to ensure the effective transmission of wind power [2,3]. Compared to the conventional power supply, wind power includes the obvious features of volatility, intermittent, and low energy density. Two flexible options have been used in the power grid to configure the transmission capacity. One solution is that transmission capacity is allocated according to the installed capacity of the wind power base, which causes over-allocation of transmission capacity, resulting in increased costs of transmission assets. Another one is to build limited transmission capacity, which introduces the waste risk of wind power due to transmission congestion, even with related low transmission investment costs. The remaining issues mentioned above are going to be solved by the Energy Storage System (Energy Storage System, ESS). The reason is that ESS has the ability to transfer power and stored energy in time. The working mode of charging at high wind power generation times and discharging during low wind power generation time has the advantages of reducing peak wind power, slowing down the demand for transmission resources, increasing the utilization rate of transmission channels, and improving the economics of transmission projects. Therefore, the collaborative planning of transmission channel capacity and energy storage is of great significance for large-scale wind power under the background of the rapid development of renewable energy and energy storage technology.

Nowadays, several research results have been achieved in the planning of power out-delivery for large-scale wind power. The authors in [4] proposed a coordinated two-level planning method for a large-scale wind farm integrated system and related regional transmission network. The contradiction between the expansion speed of transmission capacity and the speed of developing installed wind capacity is solved under the background of large-scale centralized development of intermittent wind energy. Due to a lack of ability to handle uncertainty in the traditional deterministic planning model, the authors in [5] consider the variability of wind speed and the uncertainty of demand and propose an algorithm to solve the transmission expansion planning problem in the generation period of large-scale wind power. Reference [6] modeled many uncertain factors and proposed a new expected value model of transmission network expansion planning based on DC power flow.

The optimized configuration of energy storage is an effective way to deal with the fluctuation of renewable energy output and insufficient system flexibility [7], which has been a hot topic for research. Energy storage plays a critical role in the power system, such as wind power fluctuation suppression [8], frequency response [9,10], spinning reserve [11], peak shaving [12,13] as well as mitigating congestion [14]. The energy storage system has changed the energy distribution of the original power system. Reference [15–17] provides the method of energy management and distribution. In addition, extensive and fruitful research has been conducted on energy storage and transmission grid planning for renewable energy integration. An approximate optimization method is used in [18] to achieve an optimal configuration of distributed energy storage site selection and constant capacity in the transmission grid. The long-term and short-term uncertainties of high-permeability renewable energy are solved by a joint planning method proposed in [19] for energy storage and transmission grids. The authors in [20] build a new robust minimum–max–minimum cost optimization model with the consideration of topology, aiming for joint

transmission and energy storage expansion planning where wind farms are connected to the power system considering topology optimization. Reference [21–26] provides algorithmic ideas for model optimization. Considering many costs, such as the cost of transmission grid expansion planning, energy storage construction and operation, unit combination, and wind abandonment, authors achieve the goal of comprehensive planning for wind farm installation and location, energy storage, and transmission grid expansion in [27]. However, the interaction between planning variables is still unclear from the above references. From the perspective of wind curtailment, the various functions of energy storage and transmission grids are verified in [28,29], and it is shown that energy storage is both a supplement to and a substitute for transmission lines, and the combined effect of the two is better. In the electricity market, the economy of large-capacity energy storage technology is evaluated in [30]. The fact that energy storage can mitigate transmission congestion and bring benefits, but the benefits are reduced or eliminated after the expansion of the transmission grid, is explained. Considering the energy storage life cycle benefits and return on investment helps to establish a framework for joint planning of energy storage site selection and capacity determination and transmission grid in [31]. Moreover, a dynamic joint planning method is proposed for energy storage and transmission grid under consideration of the life and performance of energy storage in [32].

All the above mentioned, there is multi-angle consideration of the problems between energy storage and transmission grids, but rarely including transmission capacity matching of a wind power base. Therefore, this paper studies the joint optimization problem of large-scale wind power transmission capacity and energy storage. The main contributions are as follows:

(1) Coordinated planning of energy storage and capacity of outgoing transmission channels of wind power bases can better deal with wind power with high amplitude and small probability, thus improving the economy of transmission engineering;
(2) The 365-day scenario is divided into high wind, stroke, and low wind conditions. The peak-valley arbitrage of energy storage in low wind conditions can reduce the unit cost of the energy storage system and overcome the problem of the high cost to a certain extent.

The rest of the paper is organized as follows. The coordination and optimization principle of transmission capacity and energy storage is introduced in Section 2. The model of coordination optimization configuration of transmission capacity and energy storage is proposed in Section 3. Section 4 presents the coordination and optimization simulations with compared results using the proposed method and other methods. Conclusions and a discussion of future work are provided in Section 5.

2 Coordination and Optimization Principle of Transmission Capacity and Energy Storage

Large-scale wind power and conventional power sources both rely on transmission channel networking, but their output characteristics are completely different from conventional generation units. There is a contradiction between the wind power transmission rate and the economics of the transmission channel.

2.1 Economic Analysis of Transmission Capacity of Wind Power Base

The output power with volatility is less than the installed capacity in the wind power base, as shown in Fig. 1 (left). Due to the temporal and spatial differences between the wind farms in the wind power base, the output power volatility will become weaker as the scale of the wind farm group increasing, and the maximum per-unit value decreases with the increasing capacity

of the wind power base. The phenomenon is called the "convergence effect" [33]. The long-term fluctuation characteristics of large-scale wind power are characterized by using the power curve of wind power, as shown in Fig. 1. When planning the external transmission channel of the wind farm group, if the transmission capacity P_{line} equals to the installed capacity of the wind farm group P_N, the transmission capacity between P_N and the maximum wind power P_{max} will not be used, which is called invalid capacity, resulting in the waste of investment, and is deteriorating as the scale of the wind farm group increasing. If P_{line} equals to P_{max}, the wind power in the neighborhood will be below P_{max} with large magnitude and short duration (only a few hours to tens of hours throughout the year). This transmission capacity with lower utilization is called "inefficient capacity." If P_{line} is lowered manually, it is easy to cause transmission congestion and a large amount of wind abandonment.
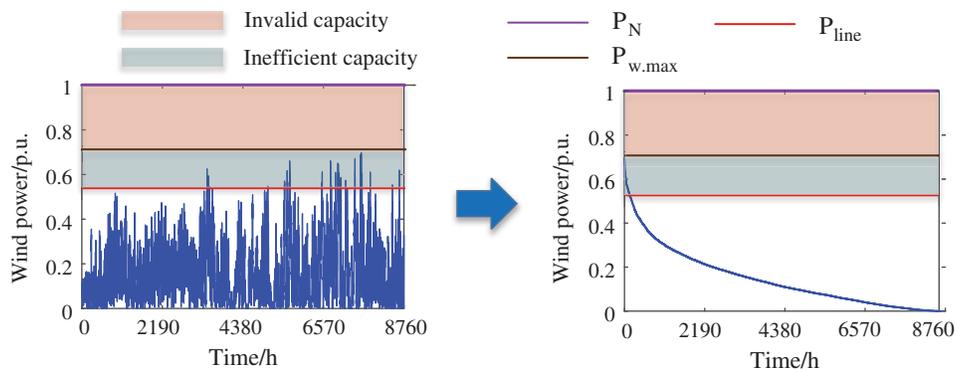

Figure 1: Economics analysis of wind power transmission capacity

2.2 Economic Analysis of Energy Storage Configuration in Outward Transmission Project

The energy storage system at the exit of the wind farm group is shown in Fig. 2. Using energy storage system to capture the "large value and small probability" wind power between P_{line} and P_{max}, it can not only reduce the transmission capacity, save the investment in transmission projects, but also alleviate the blockage and abandon wind, and better solve the dilemma of insufficient transmission capacity allocation of large-scale wind power transmission channels.
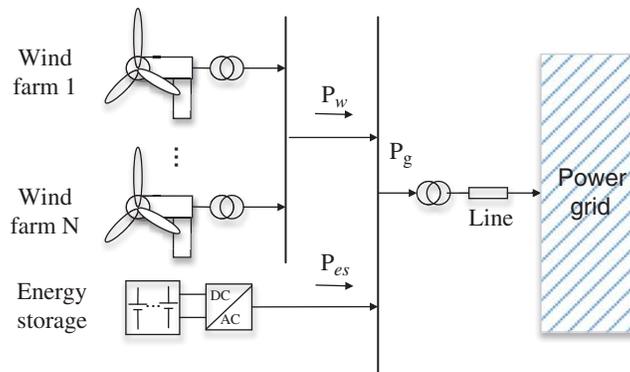

Figure 2: The sketch diagram of centralized grid-connected wind power

However, the reason why energy storage is not applied on large scale is that it has a high cost and single energy storage function for planning with difficulty in cost recovering. The economics of energy storage systems is analyzed as following when applied in large-scale centralized delivery.

Taking the wind farm group shown in Fig. 1 as an example, the maximum output value is 0.7 p.u., and the corresponding time series of output features are shown in Fig. 3. As the transmission capacity P_{line} decreasing, the decreasing trend of the blocked abandonment power value ΔP (is $P_{max} - P_{line}$), the abandonment duration T_{dur}, and the abandonment power ΔE can be noticed directly. Three types of typical operating conditions of wind power can be divided based on the relationship between wind power and transmission capacity from the output feature curve. (a) Strong wind conditions: the minimum value P_{min} of wind power for the whole day is bigger than P_{line}. There is no discharge space for the energy storage system, and wind power exceeding P_{line} will be abandoned. (b) Moderate wind conditions: the maximum value of wind power P_{max} is bigger than P_{line}, and the minimum value of wind power P_{min} is smaller than P_{line}. The energy storage system captures the abandoned wind. (c) Weak wind conditions: the maximum value of wind power P_{max} is smaller than P_{line} throughout one day, and there is no blocking and abandoning wind, as shown in Fig. 3. The occurrence times of the three-type working conditions are T_1, T_2, T_3.
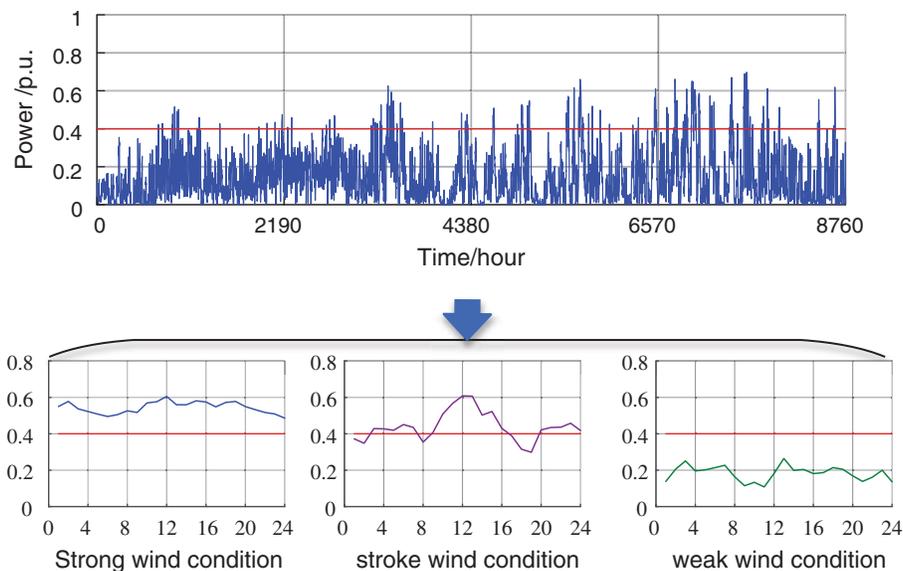

Figure 3: Three typical working conditions of wind power

When the transmission capacity P_{line} decreases from 0.65 to 0.40 by the step of 0.05, ΔP, ΔE, T_{dur}, T_1, T_2, and T_3 are shown in Tab. 1.

From Tab. 1, when the transmission capacity is 0.4, the duration time of wind abandonment is 485h, accounting for only 5.54% of the annual time, and the wind abandonment conditions (strong wind conditions, moderate conditions) is lasting a total of 89 days, accounting for 24.38% of the whole year. If the energy storage system only captures blocking and abandoning wind in the power transmission project, its working time is only T_2. The utilization rate of energy storage assets is extremely low, and the cost is difficult to recover. When coordinating the planning with

the transmission capacity, the high cost of energy storage per unit time results in a small amount of energy storage configuration, or even no energy storage.

Table 1: ΔP, ΔE, T_{dur}, T_1, T_2, and T_3 under different P_{line}

P_{line}/p.u.	ΔP/p.u.	ΔE/p.u. (Proportion of total amount)	T_{dur} /hour	T_1/Day	T_2/Day	T_3/Day
0.65	0.05	0.17 (0.01%)	8	0	6	359
0.60	0.10	1.20 (0.09%)	39	0	14	351
0.55	0.15	4.38 (0.33%)	98	0	22	343
0.50	0.20	11.78 (0.89%)	198	0	41	324
0.45	0.25	24.34 (1.84%)	312	1	60	304
0.40	0.30	43.82 (3.32%)	485	1	88	276

2.3 Energy Storage Cost Allocation Model

To improve the economic feasibility of the energy storage system, reduce energy storage cost in unit time, a cost-sharing model based on the time ratio of the multi-function tasks of the energy storage system is proposed, in which the energy storage system can participate in the auxiliary peak shaving service (or peak-valley arbitrage) of the power system in the weak wind condition, except for the blocking and abandonment of the wind in the moderate condition, improving the recovery efficiency of energy storage cost. The formula of cost allocation model is as follows:

$$I_{tot}(P_{ess}, E_{ess}) = P_{ess}K_p + K_e E_{ess} \tag{1}$$

$$\begin{cases} R_{N-0}(P_{ess}, E_{ess}) = -\lambda_1 I_{tot}(P_{ess}, E_{ess}) \\ R_{N-L}(P_{ess}, E_{ess}) = R_L(P_{ess}, E_{ess}) - \lambda_2 I_{tot}(P_{ess}, E_{ess}) \\ R_{N-P}(P_{ess}, E_{ess}) = R_P(P_{ess}, E_{ess}) - \lambda_3 I_{tot}(P_{ess}, E_{ess}) \\ \lambda_1 = \dfrac{T_1}{365}, \ \lambda_2 = \dfrac{T_2}{365}, \ \lambda_3 = \dfrac{T_3}{365} \end{cases} \tag{2}$$

where, $I_{tot}(P_{ess}, E_{ess})$ is the total investment cost of the energy storage system, and P_{ess} is the charge/discharge power of the energy storage system; E_{ess} is the capacity of the energy storage system, and K_p is the purchase cost of the unit power converter; K_e is the purchase cost per unit capacity of the energy storage system; λ_1 is the proportion of the total cost of the energy storage system under strong wind conditions; λ_2 is the proportion of the cost of the energy storage system to capture and abandon the wind under moderate conditions; λ_3 is the cost ratio of energy storage auxiliary peak shaving (peak-valley arbitrage) under weak wind conditions; $R_{N-0}(P_{ess}, E_{ess})$ is the net income of the energy storage system under strong wind conditions. Because energy storage cannot be dispatched under strong wind conditions, the net income is negative and its cost; $R_{N-L}(P_{ess}, E_{ess})$ is to capture the net income of obstructed abandonment, $R_L(P_{ess}, E_{ess})$ is to capture the income of abandonment; $R_{N-P}(P_{ess}, E_{ess})$ is the net income of peak and valley arbitrage, and $R_P(P_{ess}, E_{ess})$ is the peak and valley arbitrage income.

2.4 Transmission Capacity and Energy Storage Coordination Principle of Optimal Allocation

The essence of coordination and optimization of the transmission capacity for wind power base and energy storage system is to use energy storage to capture "large value and small probability" peak wind power, reduce the dependence of wind power on transmission capacity, thereby delaying transmission line investment. Namely, in the case of maximizing the capture of abandoned wind, it's a game between the net income of transmission and the net income of energy storage, whose goal is to maximize the comprehensive income. The variables of transmission capacity, energy storage charge/discharge power, and energy storage capacity should be optimized.

The coordination and optimization procedure of energy storage and transmission capacity is shown in Fig. 4.

Firstly, given the transmission capacity P_{line}, use the continuous output curve of the wind farm group to calculate the transmission project investment and transmission income, and then obtain the net transmission income;

Secondly, to prevent the effect of the energy storage system from being affected when switching between adjacent operating conditions, the energy storage system meets the full charge and discharge constraints within the day, that is, the state of charge (SOC) should meet: $SOC(0) = SOC(24)$. The energy storage is configured to maximize the blocking and abandonment of wind in moderate conditions. Then, according to the energy storage cost allocation model, calculate the energy storage to capture the net income of wind power. The configuration capacity E_{ess} of the energy storage system is the maximum value of the curtailed wind power captured in all moderate conditions. Among them, the energy storage for a single moderate condition is the smaller one between the charging space and the discharge space during the day. And the energy storage system charge/discharge power P_{ess} is the maximum value of charge/discharge power in all moderate conditions, The charge/discharge power of a single moderate condition is the difference between the wind power and the transmission capacity corresponding to the smaller one between the charging space and the discharge space. The equations are as follows:

$$E_{ess} = \max_{i=1}^{T_2} (E_{ess-i}) \tag{3}$$

$$E_{ess-i} = \min \left(W_{c-i}, W_{dc-i} \right) \tag{4}$$

$$P_{ess} = \max_{i=1}^{T_2} (P_{ess-i}) \tag{5}$$

$$P_{ess-i} = \begin{cases} P_{max-i} - P_{line}, & W_{c-i} \leq W_{dc-i} \\ P_{line} - P_{min-i}, & W_{c-i} > W_{dc-i} \end{cases} \tag{6}$$

where, P_{ess-i} and E_{ess-i} are the energy storage power and energy storage capacity on the i-th day in the annual moderate condition (capture of abandoned wind power); W_{c-i}, W_{dc-i} are the charging space and discharge space on the i-th day in the moderate condition; P_{max-i}, P_{min-i} are the maximum and minimum wind power on the *i*-th day in the moderate condition throughout the year.
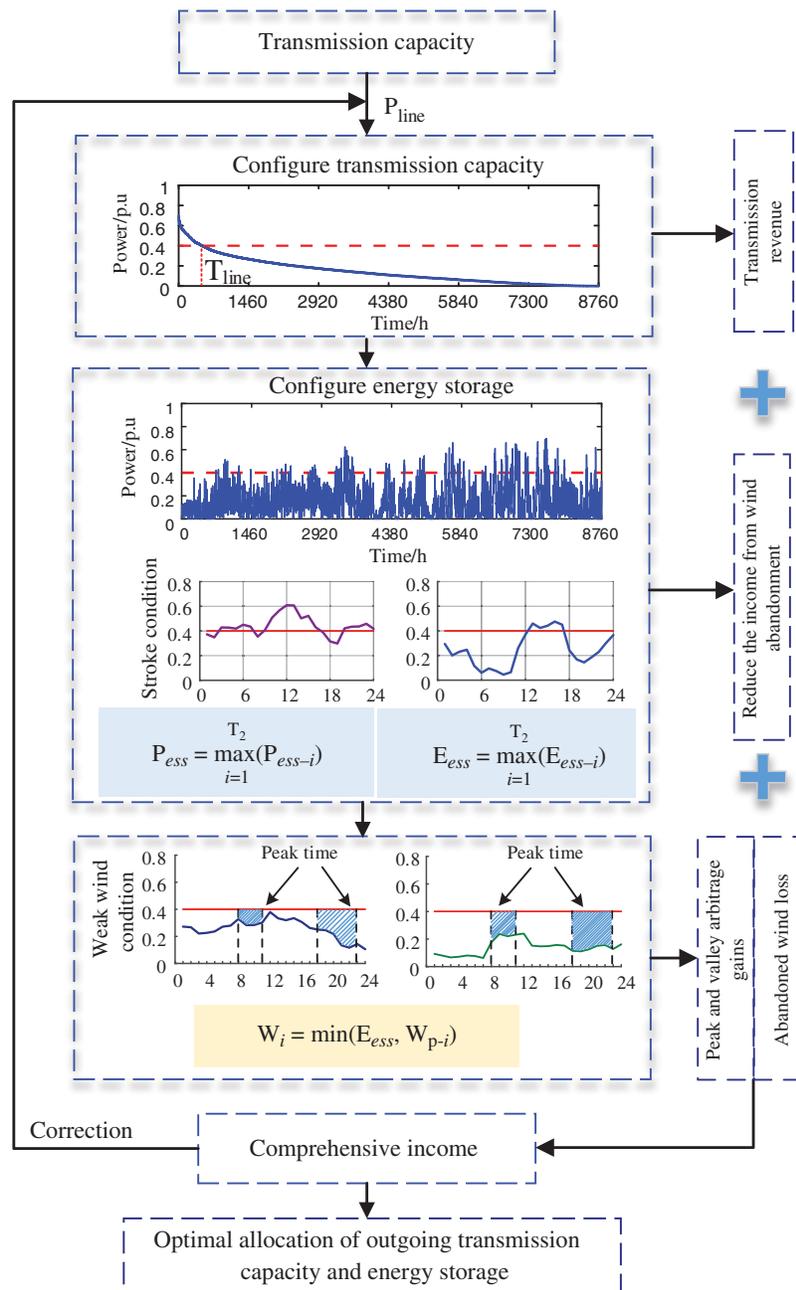
Figure 4: Coordinated optimal planning of outgoing

Thirdly, use the above-mentioned energy storage configuration to carry out peak-to-valley arbitrage under weak wind conditions to increase energy storage cost recovery efficiency. Among them, the energy storage is charged during the low load period and discharged during the peak load period. There will be no restriction when charging, and the remaining transmission capacity of the transmission line during the peak load period during discharge. Therefore, the

peak-to-valley arbitrage power is the smaller of the remaining transmission space and the energy storage capacity, that is:

$$W_i = \min\left(E_{\text{ess}}, W_{\text{p}-i}\right) \tag{7}$$

where $W_{\text{p}-i}$ is the remaining transmission power space during the peak load period on the i-th day in weak wind conditions.

Finally, the comprehensive income is calculated using variables such as power transmission income, income from capturing wind abandonment, peak-to-valley arbitrage income, and wind abandonment loss, iteratively modify the P_{line} and finally obtain a joint optimization plan for the transmission channel capacity and energy storage.

3 Coordination and Optimal Allocation Model of Transmission Capacity and Energy Storage

To facilitate the analysis of the relationship between transmission power of transmission line, energy storage power and wind power, the transmission power of transmission line, energy storage charge/discharge power, and energy storage capacity are set to continuous values, and the energy storage system capacity-to-power ratio is set as an integer. The actual project is rounded according to the optimal solution to obtain a feasible project plan.

The factors such as transmission revenue, transmission investment, energy storage system income, energy storage investment and wind abandonment loss compensation are all considered, and a coordinated optimization model of energy storage and transmission capacity is built to maximize the comprehensive benefits of transmission projects and energy storage systems.

$$\max_{0 \leq P_{\text{line}} \leq P_{\text{N}}} f = R(P_{\text{line}}) - I(P_{\text{line}}) + R_{\text{N}-0}(P_{\text{ess}}, E_{\text{ess}}) + R_{\text{N}-\text{L}}(P_{\text{ess}}, E_{\text{ess}}) + R_{\text{N}-\text{P}}(P_{\text{ess}}, E_{\text{ess}}) - L(P_{\text{ess}}, E_{\text{ess}})$$

$$\tag{8}$$

where, $R(P_{\text{line}})$ is the power grid transmission income; $I(P_{\text{line}})$ is the investment in the transmission project; $L(P_{\text{ess}}, E_{\text{ess}})$ is the value of the abandonment loss that cannot be captured by energy storage, and the wind power enterprise is fully compensated according to the wind power grid price.

Using wind power continuous power curve calculation: $R(P_{\text{line}})$, and using wind power time series power curve to calculate $R_{\text{L}}(P_{\text{ess}}, E_{\text{ess}})$, $R_{\text{p}}(P_{\text{ess}}, E_{\text{ess}})$ and $L(P_{\text{ess}}, E_{\text{ess}})$ and other variables. These variables are calculated as the following:

(1) $R(P_{\text{line}})$ is the income generated by the transmission of wind power through the transmission channel, and the calculation formula is

$$R(P_{\text{line}}) = K_{\text{r}} G_{\text{wind}} T_{\text{s}} \tag{9}$$

where K_{r} is the revenue of the unit of wind power delivered by the power transmission company; T_{s} is the payback period of the transmission investment; G_{wind} is the annual out-delivery of wind power. The continuous power curve of the used year is calculated as follows:

$$G_{\text{wind}} = P_{\text{line}} T_{\text{line}} + \int_{T_{\text{line}}}^{T_{\text{end}}} P_{\text{w}}(t) \, d(t) \tag{10}$$

where T_{line} is the continuous output time when the output power of the wind power base is higher than P_{line}; T_{end} is the total continuous output time of the wind power base.

(2) Transmission project investment $I(P_{line})$ can be calculated as:

$$I(P_{line}) = K_c P_{line} l \tag{11}$$

where K_c is the transmission project cost per unit capacity and unit length; l is the transmission distance.

(3) Energy storage system captures the benefits of blocking wind curtailment $R_L(P_{ess}, E_{ess})$.

Wind power exceeding the transmission capacity will be discarded due to transmission congestion, and this part of the wind power will be filled by thermal power. The energy storage system captures the curtailment of wind while also reducing corresponding carbon emissions. Therefore, the energy storage system will produce the benefits of increasing wind power generation and reducing carbon emissions. We can find the captured benefit using the following equation.

$$R_L(P_{ess}, E_{ess}) = (K_s + K_c) G_{cap} T_e \tag{12}$$

where K_s is the on-grid electricity price for wind power; K_c is the cost of carbon emissions per unit of electricity; T_e is the static recovery period of energy storage investment; G_{cap} is the abandoned wind power captured by energy storage.

$$G_{cap} = \sum_i^{T_2} E_{ess-i} \tag{13}$$

where E_{ess-i} is the captured and abandoned wind power on the i-th day in moderate condition.

(4) Loss value of wind curtailment that energy storage cannot capture $L(P_{ess}, E_{ess})$:

$$L(P_{ess}, E_{ess}) = (G_{lost} - G_{cap}) K_s T_s \tag{14}$$

where G_{lost} is the abandonment of wind power caused by transmission congestion, and the equation is as follows:

$$G_{lost} = \begin{cases} 0, & P_{line} \geq P_{w \cdot max} \\ \int_0^{8760} P_w(t)\,dt - G_{wind}, & P_{line} < P_{w \cdot max} \end{cases} \tag{15}$$

where $P_{w \cdot max}$ is the maximum output power of the wind power base.

(5) The cost of the energy storage system is as Eq. (1).
(6) Benefits of energy storage system peak-valley arbitrage.

The energy storage system uses the peak-to-valley price difference to conduct peak and valley arbitrage in weak wind conditions, which can be calculated as follows:

$$R_p(P_{ess}, E_{ess}) = K_p \sum_{i=1}^{T_3} W_i T_e \tag{16}$$

where K_p is the peak-to-valley price difference, W_i is the peak-to-valley charge and discharge capacity of the i-th day in weak wind conditions, calculated as Eq. (7).

4 Case Study

4.1 Calculation Conditions

Taking wind power of the wind power base located in the northeast of China as the study case, The wind power base is composed of 15 wind farms, with a total installed capacity of 2013 MW. The continuous output curve of the wind power base is shown in Fig. 1. The maximum wind power is 1403 MW, concentrated interconnection and energy storage configuration diagram, as shown in Fig. 5.
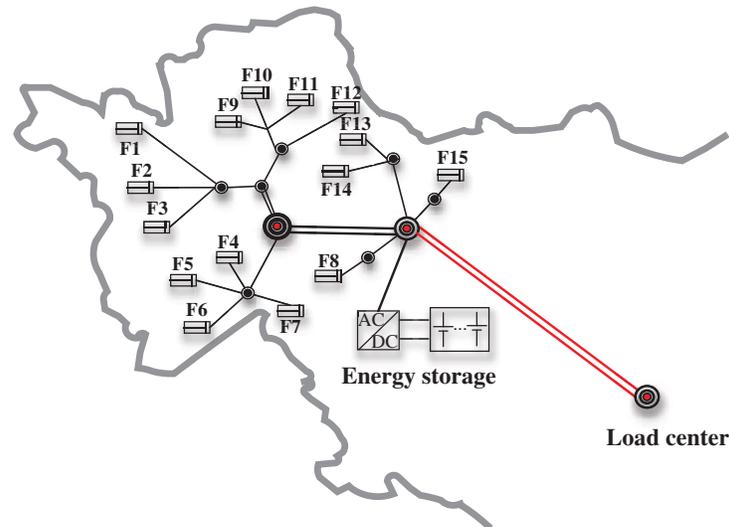

Figure 5: Wind farm cluster centralized grid

The conditions for calculation are as following:

(1) Charges for transmission of unit wind power by transmission utility.

$K_r = 0.009$ dollars/(kW·h),

(2) 220 kV integrated transmission project unit cost

$K_c = 1.513$ million dollars/(100 MW·km), Transmission distance $l = 200$ km,

(3) Power grid transmission congestion caused by wind abandon the wind loss compensation unit price (according to the wind power generation unit price calculation $K_s = 0.0908$ dollars/(kW·h). Unit power carbon charge $K_c = 0.0348$ dollars (kW·h),

(4) Unit electricity peak valley price difference $K_P = 0.0953$ dollars/(kW · h), local peak electricity price 0.1468 dollars, the valley of electricity price 0.0514 dollars,

(5) Transmission investment recovery period $T_S = 20a$,

(6) Power inverter unit cost 0.7567 million dollars/MW,

(7) Lithium-ion batteries are divided into unit capacity costs 2.27 million dollars/(MW · h), Energy storage efficiency of 80%,

(8) Investment recovery period of energy storage system $T_e = 10a$.

4.2 Coordination Optimization Results

In the case of wind power base size, the wind sources are approximately the same every year, and the relationship between wind power and transmission capacity is relatively stable. The proposed coordination optimization model can meet the requirements of planning for transmission capacity and energy storage. Transmission capacity and energy storage configuration optimization results are shown in Tab. 2.

The changing trend of each variable is shown in Fig. 6 during the optimization process. The comprehensive income increases with transmission capacity increasing, and it reaches the maximum value before transmission capacity equals 1115 MW, then it decreases with the increasing transmission capacity. Transmission income also increases with the increase in transmission capacity. When the capacity increases to the maximum wind power, the income remains constant. Transmission investment is increasing linearly. With the growth of transmission capacity, the demand for energy storage is reduced, and the working space is also compressed; when the maximum wind power of 1403 MW is reached, all wind power will be transmitted by the transmission line, without the need to configure energy storage.

Table 2: Results of coordinated allocation of transmission capacity and energy storage

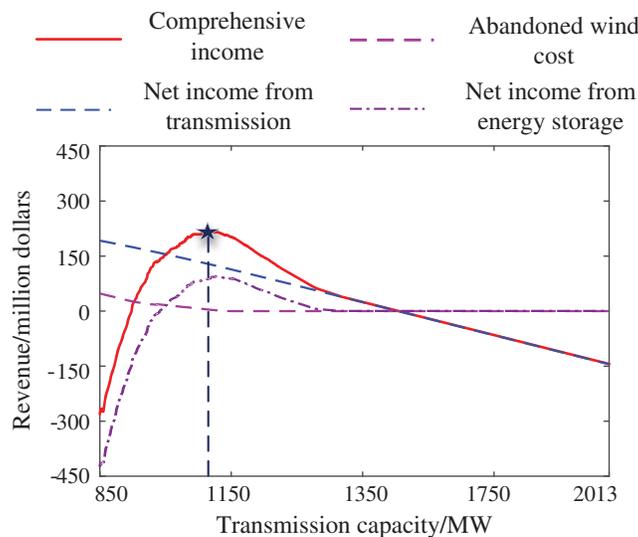| Transmission	Transmission capacity/MW	Transmission income/ million dollars	Line investment/ million dollars	Wind abandonment loss/million dollars	Comprehensive income/ million dollars
	1115	461.8644	337.1671	2.4213	
Energy storage	Capacity/MW	Capacity/MWh	Energy storage income/billion dollars	Energy storage investment/billion dollars	218.22
	280	1324	618.4927	522.5484	

Figure 6: Sketch map of optimal transmission capacity for wind power output

The optimal solution for transmission capacity and energy storage coordination is that P_{line} equals 1115 MW, in which strong wind condition is 0 day, moderate wind condition is on 27th day, and weak wind condition is on the 338th day, as shown in Fig. 7
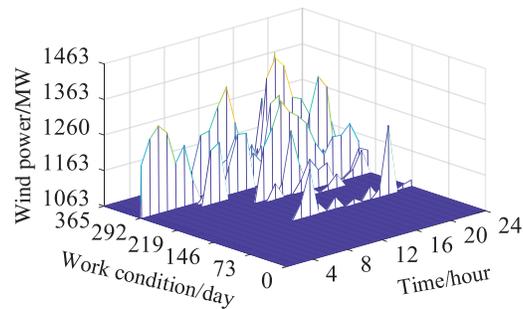

Figure 7: Wind power conditions at $P_{line} = 1115$ MW

With the development of energy storage technology, the cost drops further. The influence of energy storage continuous cost reduction on transmission capacity is analyzed as follows. Setting the cost of energy storage unit to three levels: (1) High-0.3027 million dollars/MW·h, (2) Medium-0.227 million dollars/MW·h, and (3) Low-0.1513 million dollars/MW·h. Three optimization results are calculated by using the proposed coordination planning model, shown in Tab. 3 and Fig. 8. From the comparison among the three schemes, energy storage power/capacity configuration increases as energy storage cost and transmission capacity gradually decrease.

Table 3: Optimization results of different energy storage costs

C	Low	Medium	High
Transmission capacity/MW	966	973	1063
Energy storage power/MW	437	429	340
Energy storage capacity/MW·h	2374	2312	1568
Total revenue/million dollars	657.839	481.6889	329.9031

4.3 Methods of Comparison

Under the same calculation conditions, the results calculated by the proposed coordination optimization planning model are compared with the two solutions calculated by the two methods in [33]. From Tab. 4, it shows that the full capacity planning method proposed in [33] is based on the installed capacity to plan the capacity of the transmission channel. Although no wind abandonment occurs, it has caused the over-allocation of transmission capacity and the worst economy. This method is optimized between the loss of wind curtailment and transmission investment, at the expense of a little wind curtailment in exchange for great savings in transmission investment. The method proposed in this paper adds energy storage to the planning of the power transmission project, which not only reduces the transmission capacity P_{line}, but also alleviates the occurrence of wind curtailment. At the same time, it provides a certain auxiliary peak shaving capability for the system, and the economy is optimal.
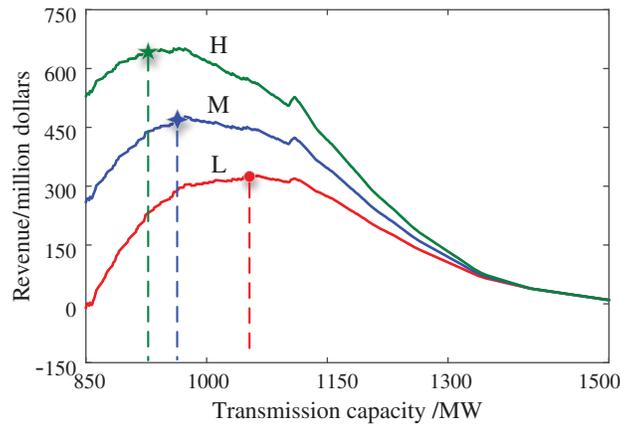
Figure 8: Optimal transmission capacity for different energy storage costs

Table 4: Technical and economic comparison of different methods

	This method	The method of reference [33]	Full capacity method
P_{line}	1115	1150	2013
Energy storage investment/million dollars	522.5484	0	0
Energy storage income/million dollars	618.4927	0	0
Transmission investment/million dollars	337.1671	348.0629	609.2615
Transmission income/million dollars	461.8644	462.1671	463.0750
Compensation for abandoned wind/million dollars	2.4213	8.1719	0
Total income/million dollars	218.22	105.9322	−146.1864

5 Conclusion

The economic impact of energy storage is analyzed in the condition where energy storage participates in the optimization of transmission capacity for large-scale wind power base. The coordination configuration optimization model of large-scale wind power transmission capacity and energy storage is proposed, in which a multi-functional cost allocation mode of energy storage is applied based on the impact analysis. The proposed method is verified by the comparison of optimal solutions with other methods.

The conclusions are drawn as follows:

(1) A multi-functional cost-sharing model for energy storage is constructed depending on the different operating tasks of energy storage, which improves the efficiency of energy storage cost recovery and overcomes the problem of high energy storage cost and difficulty in cost recovery.

(2) Compared with the method in literature [33], the coordinated optimization method for the capacity and energy storage of the outgoing transmission channel of large-scale wind power base proposed in this paper reduces the transmission capacity by 35 MW, reduces the wind abandonment loss by 575 million yuan, and increases the overall economic benefit by 11.229 billion yuan. The proposed method not only reduces the transmission capacity but also alleviates the occurrence of wind abandonment. At the same time, it provides a certain auxiliary peak regulation ability for the power system and obtains better transmission engineering benefits.

(3) The coordination and optimization model of the capacity and energy storage of large-scale wind power bases is proposed, which not only reduces the transmission capacity, but also alleviates the occurrence of wind curtailment. At the same time, it provides a certain amount of auxiliary peak regulation capability for the power system, and gains better income for the power transmission project.

(4) With the further reduction of energy storage costs in the future, the advantages of the proposed method will become more prominent, providing an effective way for the expansion planning of large-scale wind power bases.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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