
Honglin Chen 1, Hao Yu 1, Xiaojuan Yang 2,*, Yong Lin 1, Suhua Lou 2 and Sui Peng 1

1 Grid Planning & Research Center of Guangdong Power Grid Co., Ltd., Guangzhou 510060, China
2 School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
* Correspondence: xiaojuan_yang@hust.edu.cn

Abstract: There are two situations of transmission redundancy and transmission congestion when large-scale offshore wind farms send power out. The energy storage system can store the power blocked by wind power due to insufficient transmission capacity and release it in the period when the wind power output level is low. In this paper, a full-life-cycle cost model is established for energy storage, and a joint planning model for offshore wind power storage and transmission considering carbon emission reduction benefits is established, which integrates power grid transmission benefits, carbon emission reduction benefits, energy storage construction costs, transmission project construction costs and wind abandonment penalty costs. The channel construction and energy storage configuration scheme with the greatest net benefit can be obtained. The relationship between the transmission channel capacity setting and the energy storage parameter configuration under this model is studied, and the combined effect of transmission channel and energy storage system in improving the level of wind power transmission is analyzed. The sensitivity analysis of the influence of the optimal storage and transmission planning scheme of the offshore wind farms is carried out from the perspectives of transmission line engineering cost and transmission channel curve type.

Keywords: offshore wind power delivery; energy storage cost model; transmission channel capacity; joint storage and transmission planning

1. Introduction

In response to crises such as fossil energy depletion and global warming, it has become a global consensus to develop new energy sources on a large scale to increase the penetration rate and optimize the power structure based on fossil fuels to reduce carbon emissions. Wind power generation has become one of the most important new energy power generation methods at present because its technology is the most mature, and its resources are throughout the sea and land and are easily available.

With the development and application of wind power generation technology, onshore wind farms are increasingly growing in size. Due to the constraints of land resources and wind energy resources, large-scale wind farms are often located in remote areas or offshore far away from power nodes. Offshore wind power generation has the advantages of less negative impact on the environment, relatively stable wind speed, large power generation, wide space, and allowing for larger-scale wind turbine units. However, compared with onshore wind farms, its construction, installation and power transmission are technically difficult and costly. The economics of power transmission for large offshore wind farms has become a major factor affecting the development of offshore wind power.

At present, the research related to wind power is mostly focused on the uncertainty of wind power output [1–4], the reliability of wind farms [5–8] and the optimal dispatching of power system with wind power [9–12]. Only a few scholars have conducted preliminary research on the outgoing transmission of large-capacity wind power [13–17], and the related...
research is to plan the outgoing transmission capacity of wind farms from the point of view of large power grid economy. However, there is little research on determining the outgoing transmission capacity from the point of view of wind farm economy.

With regard to transmission capacity planning, the authors of [18] put forward a static optimization method to determine integrated power transmission capacity of clustering wind farms from the point of view of wind farm. The authors of [19] construct a double-level model of transmission system planning considering the capability of accommodating intermittent generation sources from the point of view of a large power grid.

With regard to the joint transmission of wind power and other power sources, from the point of view of wind farms, a capacity optimization methodology of corollary thermal sources transmitted with wind power together is proposed in [20,21]. Under the premise of wind power priority, the transmission channel is fully utilized to maximize economic benefits. Based on the time-sharing energy complementary characteristics of wind farms and concentrating solar power plants, the authors of [22] establish a capacity configuration optimization model of combined wind-CSP system for different thermal storage capacity of CSP station. From the point of view of large power grids, the multistate wind power model is adopted and the concept of residual capacity is introduced in [23], and it proposes a probabilistic model for joint delivery to simulate the process of electric power support from the sending end to the receiving end.

In the construction of offshore wind farms, the cost of transmission cables is relatively high, and the procurement and installation costs of submarine cables usually account for 8% to 12% of the total investment cost. If the wind power transmission capacity is planned according to the total installed capacity of wind farms, it is likely to cause overallocation of transmission capacity and reduce economic benefits. The energy storage system can store the power blocked by wind power due to insufficient transmission capacity and release it when the wind power output level is low, and the installation of the energy storage system is flexible and the response speed is fast. The joint application of energy storage with wind power and transmission projects can not only improve the wind power delivery level, but also smooth the fluctuation of wind power output.

In the aspect of energy storage capacity planning, firstly, the energy storage cost model is studied. A general life-cycle cost model of battery energy storage is established in [24], which is used to calculate all kinds of energy storage cost in an all-round way. In order to improve the randomness and fluctuation of wind power output and deal with the uncertainty, the joint operation model and adjustable robust optimization for the hybrid wind energy storage system are established in [25,26], respectively. In order to meet the requirements of wind power output and alleviate the impact of wind power on the power system, the optimization configuration model of a complementary hybrid energy storage system is established in [27,28]. Under the condition that the abandoned wind loss caused by insufficient transmission capacity in the process of a large-scale wind power connection is becoming more and more serious, the authors of [29] put forward an optimization method of using energy storage systems to improve wind power transmission capacity, and an economic evaluation model of transmission line benefit based on energy storage systems is established; however, in the configuration of energy storage systems, taking the outgoing transmission capacity as a known condition, there is no joint optimization of outgoing transmission capacity and energy storage system configuration.

With regard to joint storage–transmission planning, from the point of view of large power grids, the authors of [30] put forward a joint planning model of source–storage–transmission aiming at minimizing the cost of comprehensive electricity in the system. The authors of [31] have established a joint planning model of energy storage and a transmission network for improving the receptive capacity of wind power, but there is no relevant literature on the joint planning of wind power delivery transmission capacity and energy storage capacity from the point of view of wind farms.

In this paper, the simulation is carried out with the year as the cycle and the day as the unit. Originally, there were 365 sets of output data of offshore wind power, but there were
problems such as long solving time, unable to find the optimal solution and no feasible solution. Therefore, 20 output scenarios were generated according to the season by using the method of cluster analysis and the method of probability.

This paper presents two innovative points: the whole-life-cycle cost model is used to describe the investment economy of energy storage, and a joint planning model of offshore wind power storage and transmission is established to increase wind power delivery and reduce carbon emissions. This paper accomplishes two outstanding tasks: the relationship between the capacity setting of the transmission channel and the configuration of energy storage parameters under this model is studied, and the influence of the project cost of transmission line and the curve type of transmission channel on the optimal storage and transmission planning scheme of the offshore wind farm is analyzed.

The rest of the paper is organized as follows. The whole-life-cycle cost model for energy storage and the joint planning model for offshore wind power storage and transmission are established in Section 2. Section 3 presents the solution method and process of obtaining the optimal transmission capacity and energy storage configuration scheme from the above model, and then conducts the practical case study and the sensitivity analysis. Finally, Section 4 concludes the paper.

2. Models and Methods
2.1. Technical and Economic Model of Energy Storage in Offshore Wind Farm

The energy storage device in this paper refers to the battery energy storage system, which has the advantages of high energy density and fast response. The analysis of the economic characteristics of battery energy storage is beneficial to its large-scale application in offshore wind farms. The whole-life-cycle cost model is used to analyze the economy of battery energy storage.

(1) Initial investment cost of energy storage:

\[ C_{\text{Inv}} = \lambda_p P_{\text{ess}} + \lambda_p E_{\text{ess}} \]  

In Equation (1), the investment cost of energy storage system is \( C_{\text{Inv}} \); \( P_{\text{ess}} \) and \( E_{\text{ess}} \) are rated power capacity and energy capacity of energy storage, respectively; \( \lambda_p \) and \( \lambda_e \) are unit power capacity cost and unit energy capacity cost, respectively.

(2) Annual cost of fixed operation and maintenance of energy storage:

\[ C_M = \frac{\sum_{n=1}^{N_T} (\lambda_m' P_{\text{ess}} + C_{\text{labor}}) (1 + r)^t}{(1 + r)^t} \]  

\[ \lambda_m' = \begin{cases} \lambda_m, & 0 \leq t \leq N_M \\ \lambda_m e^{\lambda_n (t-N_M)}, & N_M < t \leq N_T \end{cases} \]  

In Equations (2) and (3), it is converted to the time of operation. \( \lambda_m' \) is the annual cost of fixed operation and maintenance per unit power and \( \lambda_m \) is the maintenance coefficient; and \( C_{\text{labor}} \) is the labor maintenance cost. The cost of fixed operation and maintenance is related to the type of energy storage technology and rated power, and \( N_T \) is the operation cycle of the energy storage system.

In the whole life cycle of the energy storage equipment, according to the turning year \( N_M \), the relationship between the annual cost of fixed operation and maintenance per unit of power and time can be divided into two stages. In the first stage, the maintenance coefficient is constant. In the second stage, due to the aging, wear and corrosion of the equipment in the sea environment, the maintenance coefficient increases exponentially at the rate of \( \lambda_n \). The schematic diagram is shown in Figure 1.
(3) Annual cost of energy storage auxiliary equipment:

\[ C_H = \sum_{n=1}^{N_T} \frac{\lambda_h \cdot P_{ess}}{(1 + r)^n} \]  

In Equation (4), \( \lambda_h \) is the annual cost of auxiliary equipment per unit energy capacity.

(4) Replacement cost of energy storage battery:

\[ C_{Rep} = \sum_{n=1}^{N_{rep}} \frac{\lambda_r \cdot P_{ess}}{(1 + r)^n} \]  

In Equation (5), after the battery reaches the maximum service life, it needs to be replaced and installed. \( \lambda_r \) is the unit power replacement cost, and \( N_{rep} \) is the replacement times of the energy storage battery and the corresponding year.

(5) Disposal cost of scrapping energy storage battery:

\[ C_{AB} = \sum_{n=1}^{N_{rep}} \frac{\lambda_{ab} \cdot P_{ess}}{(1 + r)^n} \]  

In Equation (6), after the battery reaches its service life, it needs to be treated innocuously, and \( \lambda_{ab} \) is the cost of scrapping per unit power.

(6) Salvage value:

\[ C_Z = \sum_{n=1}^{N_{rep}} \frac{\lambda_z \cdot C_{Inv}}{(1 + r)^n} \]  

In Equation (7), \( \lambda_z \) is the recovery coefficient, and the salvage value is also called recovery value, which can be regarded as negative cost.

Combined with the above cost types, the whole-life-cycle cost can be expressed as an equal annual value, which is shown in Equation (8).

\[ C_{ess} = C_{Inv} + C_M + C_H + C_{Rep} + C_{AB} - C_Z \]  

Compared with the initial investment cost, the whole-life-cycle cost can reflect the economy of energy storage more comprehensively.

2.2. Joint Planning Model of Offshore Wind Power Storage and Transmission

Due to the fluctuation, randomness and uncertainty of offshore wind power, even if the transmission channel capacity is set reasonably, there will still be a waste of resources due to transmission redundancy in some periods where the overall output of the wind
farm group is small, and the abandoned wind loss is caused by transmission congestion in part of the period where the overall output of the wind farm group is large. The allocation of energy storage on the source side can smooth the fluctuation of offshore wind power output, improve the offshore wind power delivery level and bring more benefits of carbon emission reduction.

2.2.1. Objective Function

In this paper, by using the equal annual value method, the optimization objective function of energy storage capacity, which can reflect the comprehensive benefit of wind storage and transmission, is constructed by comprehensively considering the factors such as power transmission benefit, carbon emission reduction benefit, energy storage construction cost, transmission project construction cost and abandoning wind penalty.

\[
\max F_S = F_{\text{wind}} + F_C - F_{\text{inv}} - F_{\text{AD}} \tag{9}
\]

In Equation (9), \( F_{\text{wind}} \) is the benefit of annual power transmission under the combined action of storage and transmission, and \( F_C \) is the carbon emission reduction benefit; \( F_{\text{inv}} \) is the investment cost of energy storage and transmission channel; and \( F_{\text{AD}} \) is the annual penalty cost of abandoning wind for offshore wind power.

The expressions of \( F_{\text{wind}}, F_C, F_{\text{inv}} \) and \( F_{\text{AD}} \) are shown in Equations (10)–(16).

\[
F_{\text{wind}} = \pi_w \times E_{\text{wind}} \tag{10}
\]

\[
C_{\text{dec}} = C_G - C_W \tag{11}
\]

\[
F_C = \pi_{\text{ex}} \times E_{\text{wind}} \times C_{\text{dec}} \tag{12}
\]

\[
F_{\text{inv}} = \alpha C_{\text{ess}} + \alpha C_{\text{line}} \tag{13}
\]

\[
\alpha = \frac{i(1+i)^{NT}}{(1+i)^{NT} - 1} \tag{14}
\]

\[
C_{\text{line}} = K_{\text{line}} L_{\text{line}} P_{\text{line}} \tag{15}
\]

\[
F_{\text{AD}} = \pi_l \times E_{\text{lost}} \tag{16}
\]

In these equations, \( \pi_w \) is the offshore wind power selling price, \( 10^4 \) CNY/MWh; \( F_{\text{wind}} \) is annual transmission electricity, MWh; \( C_G \) is the power grid unit carbon emission quota, ton/MWh; \( C_W \) is the unit offshore wind power carbon emissions, ton/MWh; \( C_{\text{dec}} \) is the unit offshore wind power carbon reduction, ton/MWh; \( \pi_{\text{ex}} \) is the carbon trading price, \( 10^4 \) CNY/ton; \( C_{\text{ess}} \) is the whole-life-cycle cost of energy storage, as shown in Equations (1)–(8); \( C_{\text{line}} \) is the investment cost of transmission channel; \( K_{\text{line}} \) is the investment cost of unit capacity per unit length of transmission channel, \( 10^9 \) CNY/(km*MW); \( L_{\text{line}} \) and \( P_{\text{line}} \) are transmission distance and offshore wind power transmission capacity, respectively; \( \pi_l \) is the abandonment price of offshore wind power, \( 10^4 \) CNY/MWh; \( E_{\text{lost}} \) is annual abandoned electricity; \( i \) is the discount rate, %. The whole-life-cycle cost of energy storage and the investment cost of transmission channel are converted into equal annual value.

2.2.2. Constraint Condition

The allocation of energy storage system and to rationally utilize the spare capacity of the transmission channel can improve the delivery level of offshore wind power.

(1) Transmission channel constraint:

\[
P_{\text{line}}^{\text{max}} = \eta P_N \tag{17}
\]

\[
P_{\text{line}}(t) = \beta_t P_{\text{line}}^{\text{max}}, t = 1, 2, \ldots, 24 \tag{18}
\]

In Equations (17) and (18), \( P_{\text{line}}^{\text{max}} \) represents the maximum power capacity of the transmission channel, and \( P_N \) is the rated capacity of the offshore wind farm; \( P_{\text{line}}(t) \) represents the actual power capacity of the transmission channel; \( \eta \) is the ratio of the
transmission channel, and $\beta_t$ is the transmission capacity coefficient; when $\eta$ is equal to 1, it means that transmission channel can be fully delivered according to the rated capacity of offshore wind power; when $\beta_t$ is always equal to 1 in the different hours of a day, it means that the transmission channel can be delivered in the type of a parallel line throughout the day. Furthermore, when the value of $\beta_t$ is not constant, the transmission protocol that follows the characteristics of load demand can be simulated.

(2) Maximum and minimum output constraint of power station:

$$P_{w\min} \leq P_w \leq P_{w\max} \quad (19)$$

In Equation (19), $P_{w\min}$ and $P_{w\max}$ are the minimum and maximum output of offshore wind turbines, respectively.

(3) Transmission capacity constraint:

$$P_w(t) + P_{out\_ESS}(t) \leq P_{line}(t) \quad (20)$$

In Equation (20), $P_w(t)$ and $P_{out\_ESS}(t)$ are the output of offshore wind farm at time $t$ and the discharge power of energy storage system at time $t$, respectively.

(4) Energy storage operation constraint:

$$-P_{cmax\_ESS} \leq P_{out\_ESS} \leq P_{dmax\_ESS} \quad (21)$$

$$E_{min} \leq E_{ess}(t) \leq E_{max} \quad (22)$$

$$E_{ess}(t) = E_{ess}(0) - \sum_{i=1}^{t} [P_{out\_ESS}(i) \times \Delta t] \quad (23)$$

$$E_{ess}(0) = E_{ess}(T) \quad (24)$$

In Equations (21)–(24), $P_{cmax\_ESS}$ and $P_{dmax\_ESS}$ are the maximum charge and discharge power, respectively, which are numerically equal to the rated power of the energy storage system; $E_{min}$ and $E_{max}$ are the lower and upper limits of real-time energy capacity, respectively, and $E_{ess}(t)$ is the real-time energy capacity.

(5) Offshore wind power delivery rate constraint:

$$\frac{E_{wind}}{E_{wind} + E_{lost}} \times 100\% \geq 95\% \quad (25)$$

3. Results and Discussion

3.1. Example Data and Parameter Setting

An offshore wind farm in a certain area of a certain province is selected. The rated installed capacity of the offshore wind farm is 93 MW, which is also used as the reference value of the relevant parameters of the transmission channel and energy storage system in this paper. In order to measure the fluctuation trend and variation law of the wind farm output power, the annual historical output data of the wind farm are analyzed, and the annual continuous output curve is drawn. As shown in Figure 2, the points on the curve correspond to the horizontal and vertical coordinates one by one. It is expressed as Equation (26).

$$T(P > P_y) = T_x \quad (26)$$

In Equation (26), $T_x$ corresponds to the abscissa of the point on the curve, indicating the cumulative number of hours, and $P_y$ corresponds to the ordinate, indicating the output level of offshore wind power.

According to $\beta_t = 1$, the transmission channel curve is in the type of a parallel line. Taking the transmission channel ratio $\eta = 0.65$ as an example, it is plotted in Figure 2. The intersection point of the annual sustainable output curve between the transmission channel and the offshore wind farm can be described as follows: when the offshore wind power output is greater than or equal to 0.65 p.u., the cumulative number of hours is
1300. According to the analysis and calculation of the chart, the following conclusions can be drawn: the annual actual generation of offshore wind power is 2271.108 p.u.; it is 1263.48 p.u. of offshore wind power sent by the transmission channel, and the annual transmission congestion is 1007.628 p.u. accounting for 44.4%.

**Figure 2.** Annual sustained output curve of offshore wind farm.

Under the standard that the abandonment rate of offshore wind power is less than or equal to 5%, when it is difficult for the transmission channel to fully supply offshore wind power because of high cost, it is extremely necessary to research and analyze the relationship between the transmission channel ratio, transmission capacity coefficient and energy storage configuration scheme, so as to configure the source-side battery energy storage system with reasonable capacity for offshore wind farms.

Based on the output data of the offshore wind farm for 8760 h in 365 days, the output scenes are clustered according to the seasons, as shown in Figure 3.

**Figure 3.** Clustering scenario of offshore wind power output by season.

The clustering scene of offshore wind power output divided by season reflects the output level of offshore wind field in each season. Each season is grouped into five categories, and the corresponding probabilities of all kinds of curves are given. The 20 offshore wind power output curves are used to characterize and simulate the characteristics of offshore wind power annual output curves, and are also used to solve the model later.

When the transmission channel follows the load characteristics, the transmission capacity coefficient should satisfy Equation (27).

$$\beta_t = P_{\text{load}}^t, \ t = 1, 2, \cdots, 24$$  \hspace{1cm} (27)

In Equation (27), $P_{\text{load}}$ is a typical daily load, p.u.; the typical daily load demand curve in this area of the province is shown in Figure 4.
The clustering scene of offshore wind power output divided by season... CW (ton/MWh) 
quantity value 0.0055 0.705 0.02 
0.5
0.6
0.7
0.8
0.9
1
1.1
0 5 10 15 20 25
load/p.u.
t Pt ==

Figure 4. Typical daily load demand curve in this area of the province.

The regulated life is set to the operation cycle of the energy storage system and transmission channel, that is, \( N_T = 20 \) years; the discount rate \( i \) is 10%. The replacement cost of the energy storage battery does not need to be considered, and the salvage value is currently not recognized for reference and is not taken into account. Other technical and economic parameters of the life-cycle cost of the energy storage battery are shown in Table 1.

**Table 1.** Technical and economic parameters of life-cycle cost of energy storage battery.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( \lambda_\text{p} ) (10^4 CNY/MW)</th>
<th>( \lambda_\text{e} ) (10^4 CNY/MWh)</th>
<th>( \lambda_\text{m} ) ( 10^4 ) CNY/(year*MW)</th>
<th>( \lambda_\text{h} ) ( 10^4 ) CNY/(year*MWh)</th>
<th>( \lambda_\text{ab} ) (10^4 CNY/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lead acid</td>
<td>150</td>
<td>125</td>
<td>15</td>
<td>300</td>
<td>1.5</td>
</tr>
<tr>
<td>lithium-ion</td>
<td>500</td>
<td>175</td>
<td>20</td>
<td>0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

According to the basic data of the current offshore wind power transmission line cost and the basic situation of electricity price and abandonment penalty from [18], the relevant parameters can be obtained, as shown in Table 2. According to the current system and policy of carbon trading market, the relevant parameters of the carbon emission reduction of offshore wind power can be obtained, as shown in Table 3.

**Table 2.** Parameters related to transmission channel and abandoning wind penalty.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( K_{\text{line}} ) ( 10^4 ) CNY/(km*MWh)</th>
<th>( L_{\text{line}} ) (km)</th>
<th>( \pi_\text{f} ) ( 10^4 ) CNY/MWh</th>
<th>( \pi_\text{w} ) ( 10^4 ) CNY/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>quantity value</td>
<td>5</td>
<td>70</td>
<td>0.06</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Table 3.** Parameters related to electricity price and carbon emission reduction.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( \pi_\text{ct} ) ( 10^4 ) CNY/ton</th>
<th>( C_\text{C} ) (ton/MWh)</th>
<th>( C_\text{W} ) (ton/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>quantity value</td>
<td>0.0055</td>
<td>0.705</td>
<td>0.02</td>
</tr>
</tbody>
</table>

3.2. Case Analysis of Joint Planning of Offshore Wind Power Storage and Transmission

The transmission channel curve is in the type of a parallel line. Taking the lithium-ion battery with higher cost parameters as an example, using the Gurobi optimization package in MATLAB software to solve the aforementioned model, the optimal solution can be obtained, and the net income is the greatest. Then, the optimal offshore wind power side energy storage configuration scheme and the comprehensive benefits of wind storage and transmission integration can be obtained by setting the transmission channel capacity to different sizes. The relevant conclusions are shown in the data in Table 4.
Table 4. Joint configuration data of offshore wind power storage and transmission.

<table>
<thead>
<tr>
<th>Channel Capacity (p.u.)</th>
<th>Net Income (CNY 10⁴)</th>
<th>P (MW)</th>
<th>E (MWh)</th>
<th>Utilization Ratio</th>
<th>Utilization Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>161.06</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.95</td>
<td>163.12</td>
<td>0</td>
<td>0</td>
<td>0.997</td>
<td>0.997</td>
</tr>
<tr>
<td>0.9</td>
<td>164.17</td>
<td>0</td>
<td>0</td>
<td>0.996</td>
<td>0.996</td>
</tr>
<tr>
<td>0.89</td>
<td>164.23</td>
<td>0</td>
<td>0</td>
<td>0.990</td>
<td>0.990</td>
</tr>
<tr>
<td>0.85</td>
<td>163.18</td>
<td>0</td>
<td>0</td>
<td>0.996</td>
<td>0.996</td>
</tr>
<tr>
<td>0.8</td>
<td>159.65</td>
<td>0</td>
<td>0</td>
<td>0.975</td>
<td>0.975</td>
</tr>
<tr>
<td>0.75</td>
<td>152.26</td>
<td>0</td>
<td>0</td>
<td>0.951</td>
<td>0.951</td>
</tr>
<tr>
<td>0.7</td>
<td>140.29</td>
<td>0.088</td>
<td>0.320</td>
<td>0.924</td>
<td>0.950</td>
</tr>
<tr>
<td>0.65</td>
<td>125.29</td>
<td>0.159</td>
<td>0.876</td>
<td>0.896</td>
<td>0.950</td>
</tr>
<tr>
<td>0.6</td>
<td>110.04</td>
<td>0.209</td>
<td>1.526</td>
<td>0.864</td>
<td>0.950</td>
</tr>
<tr>
<td>0.55</td>
<td>94.63</td>
<td>0.259</td>
<td>2.184</td>
<td>0.826</td>
<td>0.950</td>
</tr>
<tr>
<td>0.5</td>
<td>78.11</td>
<td>0.322</td>
<td>2.846</td>
<td>0.779</td>
<td>0.950</td>
</tr>
</tbody>
</table>

According to Table 4, the optimal solution is that the transmission channel is set to 0.89 p.u. without additional lithium-ion battery energy storage system. The utilization rate of offshore wind power is 99.6%, and the maximum net income is CNY 1.6417 million. The transmission benefit obtained by increasing the transmission channel capacity is less than the transmission project investment cost, and the investment cost of the transmission project saved by reducing the transmission channel capacity is less than the wind abandonment penalty.

Then, the transmission channel capacity is gradually set to different sizes; when the transmission channel capacity gradually decreases, in order to ensure that the utilization rate of offshore wind power is not less than 95%, additional energy storage is needed. When the transmission channel capacity decreases by 0.05 p.u., the power capacity of energy storage increases by 0.05–0.07 p.u., and the energy capacity increases by 0.66 p.u.

For the maintenance of energy storage equipment in the whole life cycle, this paper mainly selects the best scenario. The maintenance coefficient is always constant and the maintenance cost of energy storage is very low. The other two scenarios are discussed as follows: for the intermediate scenario where the energy storage equipment is slightly aged, worn and corroded in the later stage, the maintenance cost will increase slightly, which will reduce the net benefit, but it just has little impact on the configuration relationship between energy storage and transmission channel capacity; for the worst scenario of severe aging, wear and corrosion of energy storage equipment in the later stage, the maintenance cost is high, which will lead to an active reduction in the capacity of energy storage and an increase in the capacity of the transmission channel during system planning.

According to the offshore wind power output clustering scene, a daily output curve is selected according to the seasons. As shown in Figure 5, its fluctuation is large, and the output level is high, which is used for follow-up examples to facilitate intuitive analysis.

Take the transmission channel as 0.65 p.u. as an example. Based on the energy storage configuration scheme 0.159/0.876 given in Table 4, the daily output scenario of Figure 5 in spring is taken as an example to analyze the combined output of wind storage and transmission.

After the original output of offshore wind power is filtered through the transmission channel, the maximum output shall not exceed the upper limit of the transmission channel power capacity. When energy storage is deployed in offshore wind farms, because the energy storage has the ability to charge and discharge and the power can be transferred quickly, it is no longer impossible to utilize the part of the offshore wind power output beyond the transmission channel due to the constraints of the transmission channel; so that offshore wind power is more consumed and utilized. The actual output curve of offshore wind power is shown in Figure 6. In addition, the real-time charge and discharge power of energy storage in the process of combining wind storage is also shown in Figure 6, and the real-time energy change of energy storage is shown in Figure 7.
Combination output curve of offshore wind power storage and transmission under the type of a parallel line.

According to the statistics and data analysis of the offshore wind power industry, the length of transmission lines gradually increases, and the cost of transmission line engineering will also increase. Here, the sensitivity of offshore wind power transmission lines increases and the technical requirements for the reliability of the transmission line gradually increase. Therefore, as the length of the transmission channel gradually increases, it is becoming inevitable that the deep sea and the open sea will become the development direction of the offshore wind power industry. Therefore, as the length of the transmission channel gradually increases, it is becoming inevitable that the deep sea and the open sea will become the development direction of the offshore wind power industry.

Take the transmission channel as 0.65 p.u. as an example. Based on the energy storage charge and discharge power, energy storage can improve the delivery level of offshore wind power on the basis of the original output of offshore wind power. The actual output curve of offshore wind power is shown in Table 4. The daily output scenario of offshore wind power selected by season gives the optimal solution obtained by solving the aforementioned joint plan.

![Figure 5](image5.png)

**Figure 5.** Daily output scenario of offshore wind power selected by season.

![Figure 6](image6.png)

**Figure 6.** Combined output curve of offshore wind power storage and transmission under the type of a parallel line.

![Figure 7](image7.png)

**Figure 7.** Real-time energy change of energy storage under the type of a parallel line.
From the joint output curve of wind storage and transmission, it can be seen that energy storage can improve the delivery level of offshore wind power on the basis of transmission channel. Energy storage and the transmission channel can smooth the output curve of offshore wind power; at the same time, it can also improve the strong reverse peak regulation effect caused by the original offshore wind power output.

According to the probability and statistical analysis of the real-time charging and discharging power of the energy storage in different offshore wind power output scenarios, as shown in Figure 8, it can be seen that the probability that the real-time charging and discharging power of the energy storage is concentrated near the rated value and the probability that it is concentrated near 0 value are almost equally divided. The energy storage devices are used more effectively.

![Figure 8. Probability distribution of real-time charge and discharge power for energy storage.](image)

**3.3. Sensitivity Analysis**

**3.3.1. Construction Cost of Transmission Line**

With the vigorous development of offshore wind power, the utilization of resources will gradually become saturated, and promoting the development of offshore wind power in the deep sea and the open sea has become an inevitable development direction of the offshore wind power industry. Therefore, as the length of the transmission line gradually increases and the technical requirements for the reliability of the transmission line gradually increase, the cost of transmission line engineering will also increase. Here, the sensitivity analysis is carried out by taking the project cost of the transmission line as an example. Table 5 gives the optimal solution obtained by solving the aforementioned joint planning model of offshore wind power storage and transmission under different costs.

**Table 5. Planning schemes under different transmission line costs.**

<table>
<thead>
<tr>
<th>$K_{line}$ (km$^4$/MWh)</th>
<th>Channel Capacity (p.u.)</th>
<th>Net Income (CNY 10$^5$)</th>
<th>P/E</th>
<th>Utilization Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.89</td>
<td>164.23</td>
<td>0/0</td>
<td>0.996</td>
</tr>
<tr>
<td>10</td>
<td>0.85</td>
<td>128.24</td>
<td>0/0</td>
<td>0.989</td>
</tr>
<tr>
<td>15</td>
<td>0.81</td>
<td>94.15</td>
<td>0/0</td>
<td>0.979</td>
</tr>
<tr>
<td>20</td>
<td>0.80</td>
<td>60.99</td>
<td>0/0</td>
<td>0.975</td>
</tr>
<tr>
<td>25</td>
<td>0.76</td>
<td>29.01</td>
<td>0/0</td>
<td>0.957</td>
</tr>
<tr>
<td>30</td>
<td>0.74</td>
<td>-1.89</td>
<td>0.012/0.047</td>
<td>0.946/0.950</td>
</tr>
</tbody>
</table>

Because the cost parameter of energy storage is higher than that of transmission project, when the utilization rate of transmission channel is not less than 95%, the optimal solution will not choose to allocate energy storage with a certain capacity. With the increase in transmission line cost, the optimal solution of the planning model shifts to the direction of channel capacity reduction. If the current transmission line cost continues to increase, in order to ensure that the utilization rate of offshore wind power is not less than 95%, it can be seen that the optimal solution of the model no longer has net income, and it is more
economical to choose to allocate energy storage with a certain capacity than to increase the capacity of the transmission channel.

At this time, the transmission line cost parameter \( K_{\text{line}} = \frac{25}{30} \times 10^4 \text{CNY/(km*MWh)} \) is maintained. Taking the lead acid battery with lower cost parameters as an example, Table 6 gives the optimal solution obtained by the aforementioned joint planning model of offshore wind power storage and transmission.

**Table 6. Storage and transmission planning under lead acid battery.**

<table>
<thead>
<tr>
<th>( K_{\text{line}} \times 10^4 \text{CNY/(km*MWh)} )</th>
<th>Channel Capacity (p.u.)</th>
<th>Net Income (CNY 10^4)</th>
<th>P/E Utilization Ratio</th>
<th>Utilization Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.68</td>
<td>30.80</td>
<td>0.133/0.474</td>
<td>0.913/0.95</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>5.30</td>
<td>0.322/2.846</td>
<td>0.779/0.95</td>
</tr>
</tbody>
</table>

With the continuous development of offshore wind power technology and the innovation of energy storage technology, the cost and distance of offshore wind power transmission line project have a further increasing trend, and the life-cycle cost of energy storage equipment has a further decreasing trend. The optimal solution of the combined storage and transmission will shift to the direction of reducing the transmission channel capacity and configuring a certain capacity of energy storage device. It shows that the joint planning of offshore wind power storage and transmission has a certain practical engineering application value.

### 3.3.2. Transmission Channel Curve Type

The direct connection of offshore wind power to the power grid will affect the safe and stable operation of the power system. Configuring energy storage on the source side to make the wind power output curve follow the load characteristics can alleviate the peak regulation problem caused by connecting wind power to the grid. When the transmission channel follows the load characteristics, the transmission capacity coefficient should satisfy Equation (27). The calculation process of the example is the same as that described in Section 3.2, and the results are shown in Table 7.

**Table 7. Storage and transmission joint configuration data following load characteristics.**

<table>
<thead>
<tr>
<th>Channel Capacity (p.u.)</th>
<th>Net Income (CNY 10^4)</th>
<th>P(MW)</th>
<th>E(MWh)</th>
<th>Utilization Ratio</th>
<th>Utilization Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>123.49</td>
<td>0.109</td>
<td>0.454</td>
<td>0.913</td>
<td>0.95</td>
</tr>
<tr>
<td>0.95</td>
<td>117.83</td>
<td>0.153</td>
<td>0.661</td>
<td>0.896</td>
<td>0.95</td>
</tr>
<tr>
<td>0.9</td>
<td>111.98</td>
<td>0.199</td>
<td>0.873</td>
<td>0.876</td>
<td>0.95</td>
</tr>
<tr>
<td>0.85</td>
<td>103.52</td>
<td>0.260</td>
<td>1.149</td>
<td>0.853</td>
<td>0.95</td>
</tr>
<tr>
<td>0.8</td>
<td>93.29</td>
<td>0.305</td>
<td>1.573</td>
<td>0.828</td>
<td>0.95</td>
</tr>
<tr>
<td>0.75</td>
<td>82.90</td>
<td>0.337</td>
<td>2.058</td>
<td>0.802</td>
<td>0.95</td>
</tr>
<tr>
<td>0.7</td>
<td>72.52</td>
<td>0.368</td>
<td>2.542</td>
<td>0.775</td>
<td>0.95</td>
</tr>
<tr>
<td>0.65</td>
<td>62.13</td>
<td>0.400</td>
<td>3.027</td>
<td>0.747</td>
<td>0.95</td>
</tr>
<tr>
<td>0.6</td>
<td>51.39</td>
<td>0.451</td>
<td>3.452</td>
<td>0.714</td>
<td>0.95</td>
</tr>
<tr>
<td>0.59</td>
<td>48.01</td>
<td>0.497</td>
<td>3.460</td>
<td>0.708</td>
<td>0.95</td>
</tr>
</tbody>
</table>

According to Table 7, the optimal solution is that the transmission channel is set to 1 p.u. and a lithium-ion energy storage system with a standard unit capacity of 0.109/0.454 is required. The utilization rate of offshore wind power increases from 91.3% to 95%, and the maximum net income is CNY 1.2349 million. When the transmission channel capacity decreases by 0.05 p.u., the power capacity of energy storage increases by 0.03–0.06 p.u., and the energy capacity increases by 0.2–0.4 p.u. Taking the transmission channel capacity as 0.65 p.u. as an example, based on the energy storage configuration scheme 0.400/3.027 given in Table 7, taking the daily output scenario of Figure 5 in summer as an example, the combined output of wind storage and transmission is analyzed when the
transmission channel follows the load characteristics, and the correlation curve is shown in Figures 9 and 10.

![Figure 9](image_url)

**Figure 9.** Combined output curve of offshore wind power storage and transmission under the type of following the load characteristics.

![Figure 10](image_url)

**Figure 10.** Real-time energy change of energy storage under the type of following the load characteristics.

If the offshore wind power delivery changes the curve type of the transmission channel, it is used to follow the load characteristics to relieve the peak regulation pressure of the system. The role of real-time charge and discharge of energy storage is particularly important in this case. The actual transmission agreement signed between the offshore wind farm and the power grid is also gradually consistent with the problems discussed in this section, and the joint planning scheme for source-side storage and transmission is of great comprehensive value.

4. Conclusions

In this paper, a joint planning method of offshore wind power storage and transmission considering the benefit of carbon emission reduction is proposed, and a life-cycle cost model of battery energy storage is established, which is applied to an offshore wind farm in a certain area of a certain province. The annual output scene of offshore wind power is analyzed by cluster analysis. The feasibility and economy of the model are verified, and the practical engineering application value of the method is analyzed. The main conclusions are as follows:
When the transmission channel curve is of the parallel line type, the optimal solution is that the transmission channel is set to 0.89 p.u. without an additional lithium-ion battery energy storage system. The utilization rate of offshore wind power is 99.6%, and the maximum net income is CNY 1.6417 million. The result of this part of the research is consistent with the conclusions of [18]. When the transmission channel curve is of the type that follows the load characteristics, the optimal solution is that the transmission channel is set to 1 p.u. and a lithium-ion energy storage system with a standard unit capacity of 0.109/0.454 is required. The utilization rate of offshore wind power increases from 91.3% to 95%, and the maximum net income is CNY 1.2349 million. With the increase in the cost of transmission line engineering and the reduction in the whole-life-cycle cost of energy storage equipment, it is better to choose the scheme of reducing the capacity of the transmission channel and configuring a certain capacity of energy storage.

When the transmission channel capacity decreases by 0.05 p.u. during the parallel line type of transmission, the power capacity of energy storage increases by 0.05–0.07 p.u., and the energy capacity increases by 0.66 p.u. When the transmission channel capacity decreases by 0.05 p.u. during the transmission that follows the load characteristics, the power capacity of energy storage increases by 0.03–0.06 p.u., and the energy capacity increases by 0.2–0.4 p.u.

This paper only studies the joint planning of offshore wind power storage and transmission from the perspective of wind farms. Due to the insufficient flexibility to adjust capacity of the power grid, the actual utilization of offshore wind power in the power grid needs to be further analyzed. Therefore, the above research can be improved from the perspective of connecting offshore wind power to the grid in the future.

Author Contributions: Conceptualization, H.C.; methodology, H.Y.; software, X.Y.; validation, X.Y. and S.L.; resources, H.C.; data curation, H.Y.; writing—original draft preparation, X.Y.; writing—review and editing, H.C.; visualization, Y.L.; supervision, S.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Project of China Southern Power Grid Co., Ltd., grant number 037700KK52190012(GDKJXM20198282) and supported by research and development plan in key areas of Guangdong Province, grant number 2021B0101230004.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the reviewers for their valuable comments on this research.

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

References


