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A cost-based life-cycle pricing model for offshore wind power plants within China's carbon trading scheme

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Abstract

The development of renewable energy is showing a rapid development trend under the goal of Carbon Emission Peak and Carbon Neutrality. Offshore wind power is significant in the decarbonization of energy and the construction of future power systems. With the support and regulation of the government, offshore wind power is gradually developing on a large scale, and the pricing of renewable energy, including offshore wind power, has become a key research topic in the electricity market. In this paper, a life cycle costing-based pricing model for offshore wind power with carbon trading is constructed. First, the theoretical on-grid electricity price for offshore wind power is calculated, the sensitivity analysis of its influencing factors is then conducted, and the corresponding solutions are proposed at the end. The results show that the price of offshore wind power will gradually decrease, which has the potential to lower the on-grid electricity price and participate in the market competition.

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Keywords: Offshore wind power; Life cycle price; Carbon trade; Cost component; Sensitivity analysis

1. Introduction

Under the goal of carbon neutrality, green industrial policies have emerged all over the world, accelerating the various technological and economic developments needed for global decarbonization [1]. Xi Jinping also proposed that China will reach its carbon emission peak by 2030 and achieve carbon neutrality by 2060. As a result, it is promising for China to promote the development of renewable energy and ensure the low-carbon development of the sustainable economy [2]. According to [3], it is observed that China is very rich in wind energy resources, which is expected to support the offshore wind power with an installed capacity of more than 1 billion KW. By the end of September 2021, the total installed capacity of onshore wind power in China exceeded 500 million KW, and the cumulative installed scale of offshore wind power connected to the grid reached 13.19 million KW, ranking

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first around the world. The proportion of wind power is growing and its integration into the future power system is unstoppable [4].

The Offshore wind energy resources is characterized by the abundant resources, the high annual power generation hours, and the proximity to the load center for easy consumption. However, it is difficult to develop and maintain the offshore wind power especially with its expensive cost, which limits the large-scale development of offshore wind power. Recently, the cost of offshore wind power is gradually decreasing as the technology to manufacture offshore wind plants and collecting systems have been improved, and the layout and design of offshore wind plants is being optimized [5,6]. In addition, China has actively adopted a carbon trading mechanism in response to its dual carbon targets, so offshore wind power can also gain environmental external revenues through carbon trading [7]. Therefore, in order to promote its development, it is necessary to gradually reduce the comprehensive cost of offshore wind power generation, and develop a reasonable pricing mechanism to ensure the industry's income. The on-grid electricity price suitable for offshore wind power has been the key research topic in the electricity market. Recently, the pricing mechanisms of wind power in foreign research mainly include the fixed-price mechanism, quota price mechanism, and green price mechanism [8–10]. The fixed-pricing mechanism can stimulate renewable energy development at the initial stage of the market. However, due to the failure of introducing the appropriate market competition mechanism, it is hard to promote the offshore wind operators to reduce costs through technological improvements [8]. The quota price mechanism interferes with market transactions by forcing market players to consume a certain percentage of renewable energy, setting a ceiling on the wind power industry, and failing to fully promote industrial development [9]. The green price mechanism can effectively drive wind power companies to reduce costs but requires a high level of environmental awareness among citizens [10]. Renewable energy will also play a participate in the electricity market as offshore wind power grows rapidly. However, the existing pricing mechanisms for wind power all around the world are not suitable for the current market environment. Therefore, it is urgent to establish a reasonable pricing mechanism for wind power.

Based on the above analysis, this paper proposes an offshore wind power pricing model considering carbon trading by analyzing the cost components in the financial life-cycle of offshore wind power investment projects. The sensitivity analysis of the main factors that affect the on-grid electricity price of offshore wind power is carried out. Finally, the corresponding measures to reduce the on-grid electricity price are proposed according to the analysis results.

2. Cost components in the financial life-cycle of an offshore wind investment project

The financial life-cycle of offshore wind power includes the construction period and operation period, where the construction period is generally 2 to 3 years while the operation period is the number of years that the offshore wind plant will be in normal operation, generally about 20 years. The longer the life of an offshore wind plants, the bigger the generation capacity and the more the construction and interest costs can be shared, which is beneficial to reducing the comprehensive electricity costs.

In the financial life-cycle, the cost components of offshore wind power investment projects are divided into four parts: construction costs, operation and maintenance costs (O&M costs), loan interest and tax costs, and decommissioning and dismantling costs at the end of the project.

• Construction cost

The construction cost is an important factor affecting the price of offshore wind power, which generally includes wind turbine cost, infrastructure investment, and grid connection cost and installation cost. The difference in wind turbines also affects the amount of electricity generated and thus indirectly affects the price of electricity, so the type of turbine has an important impact on the price of electricity. The cost of infrastructure for offshore wind power plants is much higher than that of onshore wind power plants, which results in a much higher total investment in offshore wind power plant construction than onshore wind power plant. Due to the complexity of the installation process of offshore wind power plants, most of these processes have to be carried out at sea, which is technically difficult and therefore the installation costs are relatively high. The analytical estimate of construction costs is shown in Table 1.

• O&M costs

The O&M costs include the expenses for fault repair and testing and the fixed expenses for staff [11]. According to data from companies involved in offshore wind power investment projects, the average annual operation and maintenance cost for the financial life-cycle of a investment project is more than 150 RMB/kW, which is about

Table 1. Construction cost components of offshore wind power.

Construction cost components	Construction cost per capacity (RMB/KW)	Cost components ratio (%)
Wind turbines	7500∼8000	30∼45
Infrastructure	1500∼2000	10∼15
Electrical equipment	3000∼4000	15∼20
Installation and commissioning	2500∼3500	10∼15
Other costs	1000∼1500	10

2% to 5% of the initial investment. Fault repair expenses refer to the expenses incurred due to the failure of wind turbines or other equipment that need to be repaired. This cost is mainly affected by the quality of wind turbines, annual power generation, wind plant sea environment and offshore distance, etc. Fixed expenses are the regular maintenance of the wind power plant, employee salaries and welfare costs, etc. This expense is relatively fixed.

• Loan interest and tax costs

Offshore wind power has a long industry chain and large investment costs, and most offshore wind power investment projects rely on commercial loans. About 20% of the initial investment for wind plants construction comes from own funds and 80% from commercial loans, which currently carry an interest rate of 4.9% in China. In addition, wind power investment projects also need to pay enterprise value-added tax (VAT), sales tax surcharge, and enterprise income tax. Currently, the VAT rate is 6.5%, the sales tax surcharge includes the urban construction and maintenance tax and the education surcharge, which is 1% and 5% of VAT respectively, and the corporate income tax is 25%, subject to the "three exemptions and three halves" policy. As a result, the average annual tax cost is also high.

• Decommissioning and dismantling costs

For safety reasons, wind plants that have reached or exceeded their service life should be decommissioned as planned. Therefore, the decommissioning and dismantling cost at the end of the project operation life must be considered, accounting for about 6% of the initial construction cost.

3. The pricing model for offshore wind power

3.1. Dynamic economic analysis

There have been many modeling studies on the cost, investment, policy and social benefit of wind power [12]. The current methods of analyzing the electricity cost for offshore wind power are mainly the accounting cost method, the levelized cost method, and the financial life-cycle pricing method. However, the accounting cost method is not conducive to grasp the electricity price level as a whole. That is because the annual cost of wind power investment projects fluctuates greatly and electricity prices also vary greatly from year to year. The levelized cost method, although widely used, does not consider factors specific to China such as VAT and income tax, and the calculation results are not precise enough [13]. Therefore, this paper proposes the financial life cycle costing-based pricing method, which considers not only the time value of capital but also the external environmental benefits of offshore wind power by means of the carbon trading, thus improving the accuracy of pricing.

3.2. The life cycle costing-based pricing method

The financial life-cycle pricing method is an inverse application of the net present value (NPV) method. The basic principle is that the expected internal rate of return (IRR) is determined under the guidance and regulation of the government, and the internal rate is the discount rate. Make the sum of the NPV of the cash flow of the wind plant in the financial life-cycle zero, so that the revenue of offshore wind power investment projects can meet the expectation of investors. The calculation flow chart of the principle is shown in Fig. 1.

3.3. The life cycle costing-based pricing mathematical model

The financial life-cycle pricing method is a cost analysis method based on comprehensive consideration of annual cost and loan repayment in the financial life-cycle of power plant investment project. It calculates the annual cash

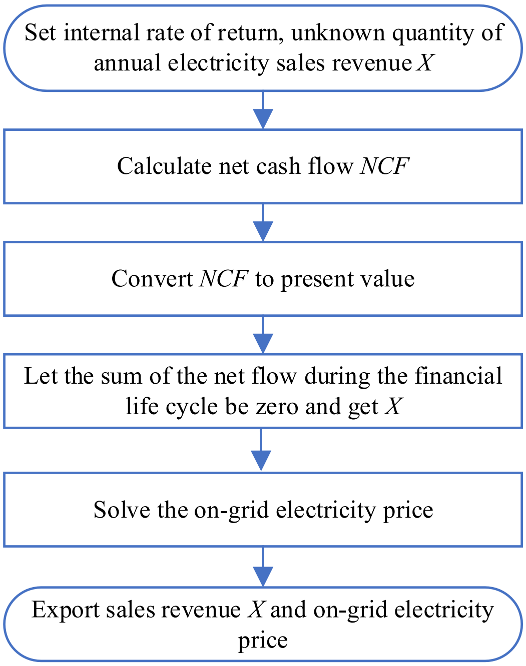

Fig. 1. Calculation flow chart for the financial life-cycle pricing method.

flow of the project and considers the financially reasonable internal rate of return for the project, which is modeled as follows:

(1) Annual net cash inflow *NCF* of offshore wind plants after commissioning

$$NCF_{\mathrm{n}(n=1,2,\ldots,N-1)} = X' + F_r - O - S - T \tag{1}$$

$$NCF_{\mathrm{n}(n=N)} = X' + F_r - O - S - T - R + V(1 - 0.25) \tag{2}$$

where X' is the revenue from the sale of electricity include tax, V is the revenue of the salvage value of the fixed assets sold after the last year of its operation period, which is subject to corporate income tax, O is the annual O&M costs, S is the annual loan repayment, T is the annual tax, and R is the decommissioning and dismantling costs.

(2) Annual loan repayment S

$$S = P_1 \frac{I(1+I)^N}{(1+I)^N - 1} \tag{3}$$

where S is the annual loan repayment by the equal principal and interest repayment, N is the loan years, P_1 is the loan, and I is the loan interest rate.

(3) Discount factor b_n

$$a_n = \frac{1}{(1+I)^n} \tag{4}$$

(4) Cash outflow P of the wind plant during the construction period

$$P = \sum_{\mathrm{n}=1}^{N} \frac{NCF_{\mathrm{n}}}{(1+I)^{\mathrm{n}}} \tag{5}$$

(5) Net present value *NPV*

$$\mathrm{NPV} = \left[\frac{\mathrm{NCF}_1}{(1+i)^1} + \frac{\mathrm{NCF}_2}{(1+i)^2} + \cdots + \frac{\mathrm{NCF}_{\mathrm{n}}}{(1+i)^{\mathrm{n}}}\right] - P = \sum_{\mathrm{t}=1}^{\mathrm{n}} \frac{\mathrm{NCF}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}} - P \tag{6}$$

(6) Rate of depreciation γ

$$\gamma = \frac{1-\eta}{N} \times 100\% \tag{7}$$

The depreciation of fixed assets adopts the straight-line depreciation method over the entire operation period of the wind farm after it has been put into operation. η is the residual value rate.

(7) VAT tax T_a and sales tax surcharge T_s

$$T_a = 0.065X \tag{8}$$

$$T_s = 0.12 \times T_a = 0.0078X \tag{9}$$

where X is the annual revenue from electricity sales excluding tax.

(8) Annual revenue X' from electricity sales with tax

$$X' = X + T_a = 1.065X \tag{10}$$

(9) Carbon trading revenue F_r

$$F_r = P_G \times \zeta \times H \times \overline{k} \tag{11}$$

where $\overline{k}$ is the average annual price of carbon trading, P_G is the power generation, and ζ is the CO2 emission reduction per unit of clean energy generation, also known as the electro-carbon conversion factor, H is used hours for the wind plant.

The above calculation steps lead to the final annual tax T and annual cash inflow NCF

$$T_i = \begin{cases} T_a + T_s & i = 1,2,3 \\ T_a + T_s + 0.125\left(X' - O - S - T_a - T_s - D\right) & i = 4,5,6 \\ T_a + T_s + 0.25\left(X' - O - S - T_a - T_s - D\right) & i = 7,\ldots,N-1 \\ T_a + T_s + 0.25\left(X' - O - S - T_a - T_s - D\right) + 0.25V & i = N \end{cases} \tag{12}$$

$$NCF_i = \begin{cases} 0.9922X + F_r - O - S & i = 1,2,3 \\ 0.8682X + F_r - 0.875(O+S) + 0.125D & i = 4,5,6 \\ 0.7442X + F_r - 0.75(O+S) + 0.25D & i = 7,\ldots,9 \\ 0.7442X + F_r - 0.75(O+S) - R + 0.25D + 0.75V & i = N \end{cases} \tag{13}$$

As the price of carbon traded in the carbon market is dynamic, carbon price revenues vary from year to year. The impact of carbon price volatility can be reduced by discounting carbon trading revenues into current value as an annual cash inflow.

4. Example analysis

4.1. On-grid electricity price calculation

The calculation example is a key offshore wind power investment project newly put into operation in 2021 in an offshore province. The coastal wind energy resources in this province are abundant, and there is huge potential for large-scale development of offshore wind power. The total installed capacity of the project is 40 MW. Each wind turbine's capacity is more than 8 MW. The annual equivalent full load generation hours are expected to be 3622 h. The total static investment is 656.123 million RMB, and the total dynamic investment is 682.704 million RMB. The capital amount is 20% of the total dynamic investment, and the remaining 80% amount is the commercial loan from the bank. The loan's annual interest rate is 4.9%, and the interest rate of the loan is calculated quarterly.

The annual repair and insurance rates for the wind plant are 2% and 0.4% of the total static investment respectively, with an expected IRR of 8%. The rate of VAT payable is 6.5%, the urban maintenance and construction tax is 1%, education surcharge is 5%, and the corporate income tax rate is 25%. However, this is following the "three exemptions and three halves" policy, which means the first three years are free of tax and the tax rate is halved for the fourth to sixth years. Other technical and economic indicators are listed in Table 2.

According to China Carbon Price Survey 2021, released by Independent Consulting Firm (ICF), the price of carbon will continue to increase under the background of industrial transformation and upgrading [14]. The forecast curve of the future carbon price is as follows (see Fig. 2):

Table 2. Technical and economic indicators for offshore wind plants.

Sequence	Projects	Data
1	Installed capacity (MW)	40
2	Annual electricity production (MW)	1.448 ∗ 10^6
3	Total depreciation of fixed assets (million RMB)	29 525.53
4	Total decommissioning and demolition (million RMB)	81 924.48
5	Conversion factor (kg/kWh)	0.336
6	Number of staff	20
7	Per capita wage (million RMB)	7
8	Benefit Factor	0.6
9	Material cost indicator (RMB/MW)	20
10	Other cost indicators	10 元/MW

Based on the financial life-cycle pricing model mentioned in Section 3, the current tax-inclusive electricity sales revenue based on offshore cost analysis considering carbon trading and capital time value is RMB 744.8809 million when the sum of the NPV is zero, and the on-grid electricity price is RMB 0.514/kWh.

Table 3. Predicted results of theoretical on-grid electricity price for offshore wind power by different sea areas in 2025.

Sea area	Investment cost per capacity (RMB/KW)	On-grid electricity price (RMB/KW)
Offshore	12 550∼14 750	0.454∼0.516
Distant sea	16 000∼17 500	0.503∼0.552

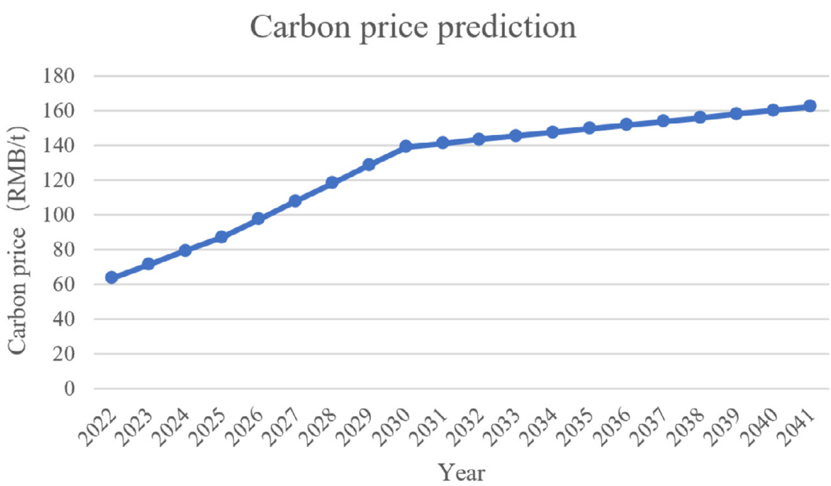

Fig. 2. Carbon price prediction curve.

According to the investment required by different offshore wind power projects and the difference of wind power resources, the theoretical on-grid electricity price of offshore wind power is calculated respectively. The results are shown in the Table 3.

From the above calculation results, it can be seen that even taking the carbon trading revenue and tax incentives into account, the on-grid electricity price cannot compete with thermal power due to its higher price, but is already lower than the current price of RMB 0.85/kWh for offshore wind power. Therefore, offshore wind power has the potential to gradually reduce price and participate in market competition. Considering the different offshore distances and water depths of wind plants in different regions, the investment costs and revenues of offshore wind plants are different, and the on-grid electricity price should be calculated and formulated separately.

4.2. Sensitivity analysis

Mathematically, sensitivity analysis is to study the influence of the change of one or several inputs x_i on the output value Y, assuming model $Y = f(x_1, x_2, \ldots, x_n)$. The purpose of sensitivity analysis on the price of offshore wind power is to find out the factors that have a greater impact on the price of offshore wind power, so as to find the most effective way to reduce the price of offshore wind power, and to provide a basis for the formulation of national policies on offshore wind power and the investment decisions of offshore wind power enterprises.

Based on factors such as costs and revenues over the financial life-cycle of an offshore wind investment project, the factors affecting the on-grid electricity price for offshore wind power can be determined, which include initial investment, annual full-load generation hours, carbon price, and IRR. The single-factor sensitivity analysis and double-factor sensitivity analysis were used to analyze the on-grid electricity price of offshore wind power respectively, to determine the influence degree of each sensitive source on the on-grid electricity price.

(1) Single-factor sensitivity analysis

The results of the single-factor sensitivity analysis for the offshore wind power investment project are shown in Fig. 3. As can be seen from the results, the initial investment in offshore wind power investment projects has the most significant impact on the on-grid electricity price. An increase of 10% in initial investment can increase the on-grid electricity price by 14.79%. The second factor influencing the on-grid electricity price is the full-load generation hours. The increase of 10% in the full-load generation hours can reduce the on-grid electricity price by 9.84%. A 10% change in carbon price and internal rate of return has a relatively insignificant impact on the on-grid electricity price.

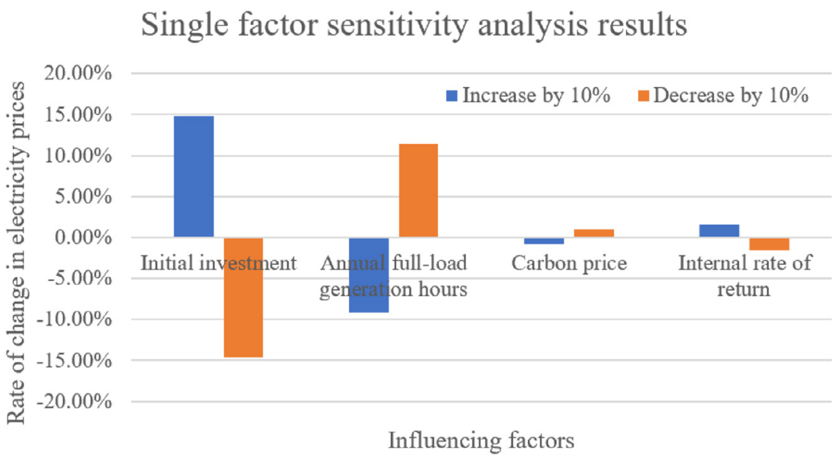

Fig. 3. Single-factor sensitivity analysis results.

(2) Double-factor sensitivity analysis

In order to analyze the mutual influence between the sensitive factors, this paper simultaneously adopts the double-factor sensitivity analysis method, and the results are shown in Table 4. When the annual full-load generation hours and the total initial investment change at the same time, the on-grid electricity price changes by −4% to +22%. Secondly, when the full-load generation hours or the initial investment change simultaneously with other factors, the on-grid electricity price changes by −7% to +17%. The results of the analysis are generally consistent with the trend of the single-factor sensitivity analysis.

4.3. Measures to promote a lower electricity price for offshore wind power

Both the single and double factor sensitivity analysis results show that the total initial investment and the annual full load generation hours have the most significant impact on the on-grid electricity price, while the carbon price and the internal rate of return also have an impact on the on-grid electricity price. Therefore, the main measures to

Table 4. Double-factor sensitivity analysis results.

Factors		Rate of price change					
		Annual full-load generation hours		Carbon price		Internal rate of return	
		+10%	−10%	+10%	−10%	+10%	−10%
Initial investment	+10%	4.09%	27.63%	14.01%	15.56%	16.93%	12.65%
	−10%	−22.57%	−4.86%	−15.56%	−13.81%	−13.62%	−15.56%
Internal rate of return	+10%	−7.78%	13.04%	0.78%	2.53%		
	−10%	−10.51%	6.42%	−2.33%	−3.31%		
Carbon price	+10%	−10.12%	10.51%				
	−10%	−8.37%	12.06%				

reduce the on-grid electricity price of offshore wind power are to increase the annual full load generation hours of offshore wind power investment projects and to reduce the initial investment of the projects.

To increase the annual full-load generation hours of wind plants, the units can be built in the sea area with abundant wind power resources. There are a few quiet wind period and high wind speed prevails in the sea area, so the utilization hours will naturally rise. In addition, it is also important to carry out preventive inspections regularly to improve reliability and reduce the downtime of offshore wind plants.

Reducing the initial investment in offshore wind investment projects can be achieved by using high-powered wind plants. With a certain installed capacity, an increase in the capacity of single units can reduce the number of wind plants, and the corresponding infrastructure, electrical equipment, and installation and commissioning costs will be significantly reduced, as well as the O&M costs in the financial life-cycle.

5. Conclusion

With the background of the global climate governance transition, China's renewable energy industry is developing rapidly, and offshore wind power has become a key development project. Based on the analysis of the cost and income of offshore wind power in the financial life-cycle, this paper proposes a pricing model for offshore wind power with the consideration of carbon market transaction and the time value of capital on the electricity price. An offshore wind power investment project in a province of China is taken as an example to calculate to offshore wind power price. Then, the single-factor and double-factor sensitivity analyses of the influencing factors of offshore wind power price are carried out, and the corresponding measures to reduce the price are proposed. However, currently the offshore wind power investment projects cannot apply for the green certificates, so the potential increase of green certificate revenue cannot be considered, nor are the additional ancillary service costs that would be incurred by integrating offshore wind power into the system. The above problems will be further improved in the future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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