LCOE Calculation Method Based on Carbon Cost Transmission in an "Electricity-Carbon" Market Environment

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Abstract

The current Chinese electricity market and carbon market are built relatively independently, without coupling and synergy, and the incoherence between the two markets is beginning to emerge. Carbon emissions costs in the carbon trading market will affect the marginal cost of renewable energy and thermal power in the electricity market, limiting market participants' profitability. In order to simulate and evaluate the changes of LCOE of renewable energy and thermal power in the "electricity-carbon" market environment, this paper presents the calculation method of carbon emission cost of thermal power and CCER benefit of renewable energy based on the relevant regulations in China, and calculates the carbon emission cost transmission rate of thermal power based on Cournot model. In addition, we proposed a method for calculating the LCOE based on the international common calculation method for LCOE, combined with China's taxation policy and the cost and benefit factors of renewable energy and thermal power in the carbon market, and proposed a method for calculating the LCOE applicable to the "electricity-carbon"

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market environment in China. The findings indicate that as a result of the influence of the carbon market, the levelized cost of energy (LCOE) cost of thermal power will increase, and the profitability of thermal power in the electricity market will be further reduced. On the other hand, the LCOE cost of renewable energy will further decrease, and its profitability will improve due to the additional CCER benefits in the carbon market.

Keywords: Electricity market, carbon market, carbon cost transmission rate, levelised electrical energy costs.

1 Introduction

Energy is the cornerstone of contemporary economic growth, and in the past few years, as the economy throughout the world has expanded at a rapid pace, so has the demand for energy in a number of different countries. At this point in time, the primary sources of energy in the globe are still fossil fuels such as coal, oil, and natural gas. Other kinds of energy are still in their infancy. China's resource endowment determines its coal-based energy structure, and the power industry has also developed a coal-dominated power supply system. China's total carbon emissions in 2019 were 10.2 billion tonnes, with 4.2 billion tonnes, or approximately 37%, coming from the electricity sector. The carbon emissions of China's power sector clearly demonstrate the significance of pursuing low-carbon power development and that the power sector should be the primary battleground for reducing carbon emissions. The carbon emissions of China's power sector fully illustrate the importance of implementing low-carbon power development, and that the power sector should be the main battleground for carbon emission reduction. Since 2011, China has been running a series of pilot carbon trading markets. In December 2017, the National Development and Reform Commission issued the National Carbon Trading Market Construction Programme (Power Generation Sector), which marked the official launch of the country's national carbon emissions trading system. The goal of "carbon peaking and carbon neutrality" was proposed by President Xi Jinping during the general debate of the 75th session of the United Nations General Assembly on September 22, 2020. On July 16, 2021, the national carbon trading market was officially launched, marking the official foundation for the simultaneous construction of China's electricity and carbon markets.

International experience with carbon markets indicates that the operation of the carbon market mechanism has had an effect on electricity market pricing in situations where power is highly marketized. Several studies have demonstrated that in the early stages of the EU carbon market, a significant portion of the cost of free carbon quota allocation was passed on to electricity prices, resulting in higher electricity prices for consumers and additional "windfall" profits for power producers, which could be mitigated to a degree by carbon taxes or quota auctions [1]. With the progressive expansion of the carbon trading market, a great deal of research has been undertaken on carbon cost transmission, and the results demonstrate that carbon costs are transmitted to power prices [2], While a large number of scholars have established theoretical models and conducted research work on the basis of verifying the robustness of model estimates in order to further quantitative analysis of carbon cost transmission rate, the results show that at least 80% of the carbon cost is passed on to electricity prices [3, 4], According to a research of the German carbon trading market, the cost of carbon is nearly entirely reflected in the price of energy [5].

Literature [6] introduced the calculation paradigm and calculation method of carbon emission cost transmission, as well as the advantages and disadvantages of various paradigms, among which the Cournot-Nash equilibrium model was based on the classical paradigm of carbon emission cost transmission. Allaz-Vila competition is introduced in literature [7]. Under certain assumptions, a change in unit output of one company is believed by the company to stimulate a 0.5 change in output of the competitor in the other direction. Literature [8] studied the intensity of competition in different degrees between Cournot and Bertrand cases based on the positive tilt of the predicted supply function. Literature [9] uses the "auction" method to analyze the impact of market structure on the transmission of carbon dioxide cost to electricity price.

From a domestic standpoint, the markets for carbon trading and energy are growing faster, and the market-oriented reform is releasing stronger signals of competition, which domestic researchers have also thoroughly researched. Literature [10] analyses the quota allocation mechanism, market benefits and shortcomings of regional carbon trading markets, and constructs a coupling mechanism between carbon trading markets and electricity markets in the region. According to some studies [11], the carbon cost transmission rate is connected to the structure of the energy market, the degree of perfect competition in the electricity supply market, and the allocation of carbon allowances, and that the greater the number of power plants, the greater the market competition, and the lower the carbon cost transmission rate in the case of an elastic price of electricity demand [12], and the results of the studies essentially indicate that the carbon cost transmission to the electricity price process causes changes in electricity prices and social welfare [13, 14]. There is an interactive effect between electricity prices and supply demand, with studies [15] showing that the demand for carbon allowances by power producers increases with increased electricity generation, and that under certain conditions of supply, thermal power producers do not hold enough allowances and therefore expect to purchase more, with an increase in excess demand and higher carbon prices, leading to a reduction in conventional energy generation. The impact of carbon pricing on the equilibrium outcome of the electrical market is studied in the literature [16]. Using the carbon price to build a model of electricity market generation costs and conduct equilibrium analysis. The literature [17] investigates the impact of emissions trading on market clearing outcomes, develops an equilibrium model of the electricity market that includes emissions trading, provides the price composition of emissions trading.

Taking Guangdong's carbon trading market and electricity market as examples [18], China established a power generation electricity cost model-LOCE (levelised cost of electricity generation) [19–22], simulated and analysed the carbon price transmission to electricity price scenarios in the carbon trading market, and carried out a study on the coupling impact of the electricity market and carbon trading market. The literature [23–25] qualitatively analyses the interaction between the power market and the carbon trading market, then quantitatively analyses the coupling relationship between the carbon trading market and the power market in the power industry, and analyses the results of the coupling between the carbon trading market and the power market by building a carbon price generation model and power production simulation. Literature [26] given a linkage mechanism between the electricity market and the carbon trading market based on electricity consumption side carbon emission factors is proposed. By introducing electricity emission factors under the market-based mechanism, the proposed method aims to increase the desire of electricity customers to pay for low-carbon electricity, thereby improving the general competitiveness of low-carbon electricity. The research presented in [27, 28] takes into account the principles of the electricity market as well as the market mechanism for the issuance of carbon rights and allowances in order to design a joint electricity and carbon operation process and model. Following this, a quantitative verification of the carbon electricity market mechanism is performed using the designed carbon electricity operation model and market mechanism.

2 Renewable Energy and Thermal Power Carbon Cost Transmission Model

2.1 Accounting for Carbon Emissions From Thermal Power

Carbon emissions from thermal power plants in China are broken down into three categories, according to the relevant Chinese policy documents: combustion, the elimination of sulfur dioxide, and net carbon emissions from purchased energy. In general, FGD approaches for thermal power units can be broken down into one of three categories: pre-combustion, in-combustion, or post-combustion. Post-combustion sulfur dioxide removal, more often known as flue gas elimination is one of them. The removal of sulfur dioxide can be broken down into the following five categories, based on the type of sulfur dioxide agent being used: calcium Sulphur dioxide elimination, magnesium Sulphur dioxide elimination, sodium Sulphur dioxide elimination, ammonia Sulphur dioxide eliminationand organic alkali Sulphur dioxide elimination. The most common method used in China is calcium Sulphur dioxide elimination, accounting for over 93.7% of the total. This method is therefore suitable for accounting for carbon emissions from post-combustion calcium Sulphur dioxide elimination in thermal power units. The following is the formula for the calculation:

$$E = E_{Burning} + E_{Desulphurisation} + E_{Purchase} \tag{1}$$

Where $E_{Burning}$ is carbon emissions produced by thermal power plants during the combustion process; $E_{Desulphurisation}$ is Carbon emissions from Desulphurization for thermal power units; $E_{Purchase}$ is Net purchased electricity carbon emissions for thermal power units.

$$E_{burning} = (ap^2 + bp + c) \times NCV_i \times 10^{-6} \times CC_i \times OF_i \times \frac{44}{12} \tag{2}$$

Where NCV_i is the average amount of low-level heat that a fossil fuel may provide; CC_i is carbon content expressed as a percentage of a fossil fuel's total calorific value; OF_i is the ratio of the molecular weight of carbon to the weight of carbon dioxide molecules.

$$E_{Desulphurisation} = \frac{\frac{64}{32} \times (\mathrm{ap}^2 + \mathrm{bp} + \mathrm{c}) \times 0.9 \times \mathrm{S} \times \frac{100}{64}}{F_t \times S_t} \times EF_K \tag{3}$$

Where S is the total Sulfides content of the coal; F_t is the purity of the carbonate; S_t is the calcium to sulfides ratio of the carbonate; EF_K is Emission factors for carbonate at complete Desulphurization.

$$E_{purchase} = AD \times EF \tag{4}$$

Where AD is the net purchased power of enterprises and EF is the annual average power supply emission factor of the regional grid, divided according to regions such as Northeast and North China.

Because thermal power generates net purchased power only in rare cases, and the total amount of net purchased power is usually small, net purchased power can be ignored when accounting for carbon emissions from thermal power units.

2.2 Carbon Quota Calculation for Thermal Power Units

According to the “Notice on the Work Related to the Allocation of National Carbon Emission Trading Quotas for the Years 2021 and 2022” of the Ministry of Ecology and Environment of China, carbon quotas for thermal power units t are allocated using the baseline method, and are divided into conventional coal-fired units above 300 MW class, conventional coal-fired units of 300 MW class and below, non-conventional coal-fired units such as coal gangue-fired units, and gas-fired units in four categories. The carbon quota allocation method for thermal power units is as follows:

$$A = A_e + A_h \tag{5}$$

Where A_e is the total unit quota, A_h is the unit generation quota and is the unit heating quota.

$$A_e = Q_e \times B_e \times F_l \times F_r \times F_f \tag{6}$$

Where Q_e is the unit power supply; B_e is the unit power supply base value; F_l is the unit cooling mode correction factor; F_r is the unit heat supply correction factor and F_f is the unit output factor correction factor.

$$A_h = Q_h \times B_h \tag{7}$$

Where Q_h is the unit’s heat supply; B_h is the heating reference value for the category to which the unit belongs.

The benchmark values for electricity and heat supply set by China have undergone a number of amendments and changes. The most recent baseline values for the supply and heating of the units are as follows, as stated by China’s 2019–2020 National Implementation Plan for Establishing and Allocating the Total Amount of Carbon Emission Trading Quotas (Power Generating Sector), which can be found here:

Table 1 Thermal power unit supply-heat benchmark values

Type of Unit	Range of Unit Types	Reference Values for Power Supply	Heat Supply Base Value
1	Conventional coal-fired units above 300 MW class	0.877	0.126
2	Conventional coal-fired units up to 300 MW class	0.979	0.126

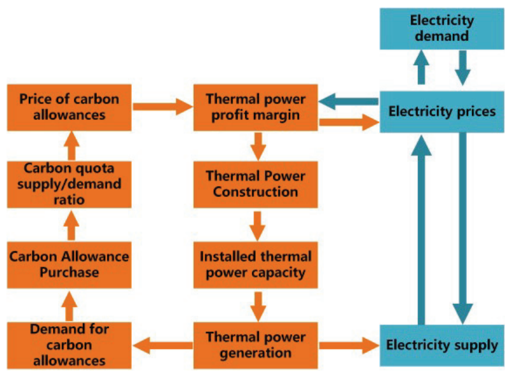

Figure 1 Thermal carbon market cost structure.

2.3 Thermal Power Cost of Carbon Transmission Model

The degree to which the cost of carbon dioxide emission allowances that are used to generate energy is passed on to those prices determines the amount to which the cost of carbon trading has an impact on the prices of electricity. Whereas the cost of carbon is not fully passed through into the electricity market, the carbon cost pass-through rate CPR will vary depending on the competitive structure of the market.

The impact that the electricity market and the carbon market have on thermal power units is depicted in the diagram below. During the course of their operation, thermal power plants will invariably be impacted by the costs of carbon trading that are imposed by the presence of the carbon market. This is because the market for the trading of carbon emissions exists. Therefore, it is necessary to include this cost in the LCOE measurement process to obtain more accurate results.

Assuming a Gounod competitive environment in the Chinese electricity market, where each power producer in the market independently specifies its own generation strategy. The marginal cost to the power producer at this point, MC_i, is as follows, with the impact of China's carbon trading market

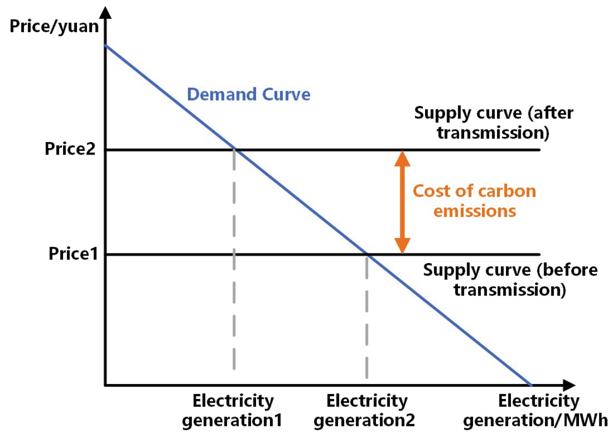

Figure 2 Carbon cost transmission principle (perfectly competitive market).

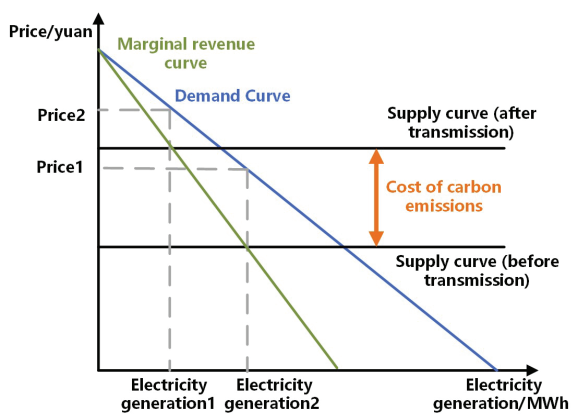

Figure 3 Carbon cost transmission principle (monopoly market).

being taken into consideration:

$$MC_i = C_i'(q_i) + CO_i \tag{8}$$

Where: q_i is the amount of electricity generated by electricity producer i(i = 1,2,...,n; n = 2); CO_i is marginal cost of carbon emissions.

As shown in Figure 1, assuming that the state of competition in the market tends towards perfect competition, and assuming that producers maximise their profits, then the marginal revenue and market price of producers at this time will increasingly tend towards marginal cost, so that under the same conditions, the cost of carbon emissions will generate a higher transmission rate, even tending towards 100% transmission.

As can be seen in Figure 3, in markets that are not fully competitive, generators will utilize their market power to raise prices to the point where those prices will be greater than the generators' marginal costs. This means that these producers' marginal revenue and marginal cost differ from their output price because they can affect the market price by modifying their output. This leads to an increasing tendency towards a carbon cost transmission rate of 50%.

Based on the above judgement, we can conclude that:

$$q_i p'(q_i + Q_{-i}) + p(q_i + Q_{-i}) - c_i'(q_i) - CO_i = 0 \tag{9}$$

Where: $Q = q_i + Q_{-i}$ is the aggregate amount of generation capacity that can be produced by all of the generators in the market for energy; Q_{-i} is the amount of electricity generated by generators other than generator i; p' is the inverse demand function of the market price of electricity, i.e. the amount of electricity generated q_i; $p'(q_i + Q_{-i})$ is the first order derivative of generation q_i with respect to the market price of electricity. Because different power producers emit different amounts of carbon dioxide into the atmosphere, the equilibrium conditions that must be met for the overall electricity market in order to maximize profits while adhering to the environmental regulations that govern China's carbon emissions trading market are as follows:

$$Qp'(Q) + np(Q) - \sum_j c_j'(q_j) - \sum_j CO_j = 0 \tag{10}$$

Because a power producer's carbon intensity is proportional to the generating capacity of its generating units, the marginal cost of a power producer's carbon emissions is also proportional to the generating capacity of its generating units, $q_j = q_j(CO_i)\ i, j = 1, 2, \ldots, n$. Taking the partial derivative of cc_i yields:

$$(n+1)p'(Q)\frac{dQ}{dCO_i} + Qp''(Q)\frac{dQ}{dCO_i} - \sum_j c_j''(q_j)\frac{dq_j}{dCO_i} = 1 \tag{11}$$

Carbon cost transmission rate:

$$CPR_i = \frac{dp}{dCO_i} = p'(Q)\frac{dQ}{dCO_i} \tag{12}$$

This results in:

$$CPR = \frac{dp}{dCO_i} = \frac{p'(Q)}{(n+1)p'(Q) + Qp''(Q) - nc''(Q/n)} \tag{13}$$

In an actual electricity market environment, where each generator is generally of a different size, the marginal cost of a generator is closer to non-linearity. For computational convenience, this paper assumes that the marginal cost of generating electricity for a generator is a fixed constant $c''(Q/n) = 0$, i.e. The cost of the generator's carbon transmission rate, CPR, can then be expressed as:

$$CPR = \frac{dp}{dCO_i} = \frac{1}{(n+1) + Q\frac{p''(Q)}{p'(Q)}} \tag{14}$$

Where. $\frac{p''(Q)}{p'(Q)}$ denotes the elasticity of the electricity demand curve and it can be seen that there is a strong link between the carbon cost transmission rate CPR and the number of generators participating in the market, the amount of power that is generated in addition to the elasticity of the demand curve for electricity among market consumers. As a matter of thumb, the carbon cost transmission rate increases in proportion to the degree to which demand is elastic.

(1) *Electricity demand is linear*:

$$CPR = \frac{1}{n+1} \tag{15}$$

Where n represents the degree of competition in the market. When the market is perfectly competitive, n $= \infty$; when the market is perfectly monopolistic, n $= 1$.

(2) *Electricity demand is isoelastic*:
Assume that the non-linear demand function for electricity is: $P(Q) = P_0(Q/Q_0)^{-1/a}$, $-\alpha$ is the electricity demand elasticity ($\alpha > 0$), Q_0 and P_0 are the electricity market clearances and tariffs for the no carbon cost scenario. Taking the first and second order derivatives of the electricity demand function and substituting them into the equation gives:

$$Q\frac{p''(Q)}{p'(Q)} = -\frac{1}{\alpha} - 1 \tag{16}$$

In turn, it is possible to obtain:

$$CPR = \frac{dp}{dCO_i} = \frac{\alpha}{n\alpha - 1} \tag{17}$$

There is a correlation between the number of generators that are active in the electrical market and the elasticity of the demand for power, both of which influence the carbon cost transmission rate. The lower the number of generators, the more competitive the market tends to be towards monopoly; the higher the number of generators, the more competitive the market tends to be towards perfect competition.

In the actual operation of the electricity market, most of the loads tend to be isoelastic, so this paper uses a carbon cost transmission model with constant marginal cost of thermal power and isoelastic demand elasticity of consumers to calculate the cost transmission rate of thermal power carbon emissions:

$$F_f = (A - E) \times C_p \times CPR \tag{18}$$

Where A is the thermal unit carbon allowance, E is the thermal unit carbon accounting volume; C_p A is the average carbon market transaction price and CPR is the thermal unit carbon cost transmission rate.

3 Renewable Energy Carbon Market Revenues

The levelized cost of electricity (LCOE) is the unit cost of electricity generated in the NPV $= 0$ scenario throughout the life cycle of a power generation project, and is often used in the initial construction phase of a project. In this paper, we take into account the "three exemptions and three halves" policy of renewable energy, the profitability of renewable energy in the CCERs market, and propose a renewable energy LCOE calculation method that is applicable to the "electricity-carbon" market environment in China. The LCOE calculation method for renewable energy is proposed.

Under Chinese regulations, the national Certified Voluntary Emission Reductions (CCERs) for renewable energy plants require additionality certification, i.e. the renewable energy IRR must be less than the national benchmark IRR of 8%. Many existing wind farms have IRRs of less than 8%, or even less than 7%, and are in a loss-making situation. Therefore, this paper assumes that the wind farm IRR taken is less than the national benchmark IRR of 8% and gives a methodology for accounting for wind farm CCERs in conjunction with national regulations.

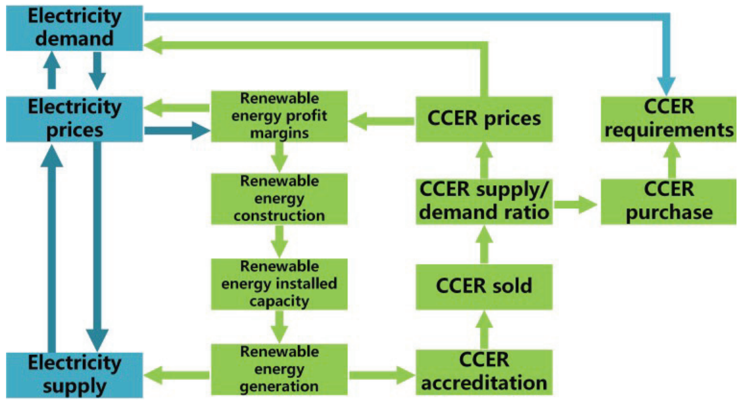

Figure 4 Renewable energy carbon market revenue structure.

As shown in Figure 4, there are additional benefits for renewables in the carbon market through CCERs, which will have an impact on the cost of renewables.

The CCERs for renewable energy are calculated as follows:

$$EF_y = BE_y - PE_y \tag{19}$$

Where EF_y is the amount of emission reduction in year y, BE_y is the emissions used as a baseline in the year; PE_y is emissions from the project for the year y.

$$BE_y = EG_{PJ.y} \times EF_{grid,CM,y} \tag{20}$$

$$EF_{grid,CM,y} = EF_{grid.OM.\mathrm{y}} \times W_{OM} + EF_{grid.BM.y} \times W_{BM} \tag{21}$$

Where $EG_{PJ.y}$ is the net feed-in electricity generated by renewable energy plants in year y; $EF_{grid,CM,y}$ is emissions from the project for the year y; $EF_{grid.OM.\mathrm{y}}$ is the marginal emission factor for the year y's electricity production; W_{OM} is the marginal emission factor weight for electricity; $EF_{grid.BM.y}$ is the marginal emission factor for capacity in year y; W_{BM} is the marginal emission factor weight for capacity.

In summary, the renewable energy carbon market benefits:

$$U_r = -EF_y \times C_{CCER} \tag{22}$$

Where C_{CCER} is CCER market prices.

4 The Specific Process of Calculating the Thermal Power LCOE Model

Since the current Chinese electricity market and carbon market are being built simultaneously, thermal power will be affected by the cost of carbon emissions from the carbon market, and the marginal cost in the electricity market will change. In this paper, the carbon emission cost of thermal power in the carbon market is considered, and the carbon emission cost transmission rate of thermal power under different market structures is also calculated based on the Cournot-Nash model to obtain the calculation method of thermal power LCOE under the competitive market environment.

(1) *Initial investment cost of thermal power*:

$$I_f = C_{f,a} + C_{f,b} \tag{23}$$

Where $C_{f,a}$ is thermal power equipment acquisition costs, $C_{f,b}$ is thermal power construction costs.

(2) Thermal power operating costs:

$$R_f = \sum_{n=1}^{N} C_{f,d}(1+i)^{-n} \tag{24}$$

Where, $C_{f,d}$ is Operating costs of thermal power in year n.

(3) Thermal Power Loan Interest Rate Costs:
The thermal power loan is carried out with equal principal and interest repayment, and the loan interest rate is taken from the People's Bank of China's latest adjusted benchmark long-term loan interest rate of 4.9% in 2019.

$$U_f = \sum_{n=0}^{Nd} U_{f,n}(1+i)^{-n} \tag{25}$$

$$U_{f,n} = \frac{L}{Nd} + \left(L - \frac{L}{Nd}n\right) \times R_f \tag{26}$$

Where $U_{f,n}$ is the interest on the loan that must be paid in the nth year that the thermal power plant is in operation; Nd is the number of years remaining on the financing for the thermal power plant; L is the total amount of power plant loans; R_f for power plant loan rates.

(4) Thermal power tax costs:
The value-added tax rate is 13%; income tax rate is 5%; business tax rate is 6%, education surcharge, city construction fee tax rate is 6%

$$T_f = \sum_{n=0}^{N} T_f(1+i)^{-n} \tag{27}$$

$$T_{f,n} = \sum_{n=0}^{N} (T_{f,value} + T_{f,incomes} + T_{f,sales} + T_{f,build} + T_{f,education})(1+i)^{-n} \tag{28}$$

Where T_f is Taxation of thermal power units in year n; $T_{f,value}$ is VAT; $T_{f,sales}$ is sales tax and surcharge; $T_{f,incomes}$ is corporate income tax; $T_{f,build}$ is urban construction and maintenance tax; $T_{f,education}$ is education Surcharge.

(5) Thermal power environment costs:

$$F_f = \sum_{n=1}^{N} F_{f,n}(1+i)^{n} \tag{29}$$

(6) Thermal power depreciation tax credit:
Thermal power units are depreciated according to the linear depreciation method.

$$V_f = \sum_{n=1}^{Nz} V_{f,n}(1+i)^{-n} \tag{30}$$

$$V_{f,n} = \frac{(1-VI)}{N} \times 100\% \tag{31}$$

Where $V_{f,n}$ is Tax credit for depreciation of thermal power units in year n; VI is the estimated net salvage rate.

(7) Residual value of thermal power:

$$G_f = G(1+i)^{-Nz} \tag{32}$$

Where G is Residual value of thermal power.

(8) Thermal power generation:

$$E_f = \sum_{n=1}^{N} E_{f,n}(1+i)^{-n} \tag{33}$$

Where $E_{f,n}$ is Generation of thermal power in year *n*.

In summary, the thermal power LCOE calculation model is:

$$LCOE = \frac{I_f + R_f + U_f + T_f + F_f - V_f - G_f}{E_f} \tag{34}$$

5 Renewable Energy LCOE Calculation Model

This paper considers the benefit of renewable energy in the CCER market and transfers it to the electricity market and obtains the calculation method of renewable energy LCOE under the synchronous construction environment of "electric-carbon" market.

(1) Initial investment cost of renewable energy:

$$I_r = C_{r,a} + C_{r,b} \tag{35}$$

Where $C_{r,a}$ is renewable energy equipment acquisition costs, $C_{r,b}$ is renewable energy construction costs.

(2) renewable energy operating costs:

$$R_r = \sum_{n=1}^{N} C_{r,d}(1+i)^{-n} \tag{36}$$

Where, $C_{r,d}$ is Operating costs of renewable energy in year n.

(3) Renewable energy Loan Interest Rate Costs:

The renewable energy loans are subject to equal principal and interest, and the loan interest rate is taken from the latest adjustment of the long-term lending benchmark interest rate of 4.9% by the People's Bank of China in 2019.

$$U_r = \sum_{n=0}^{Nd} U_{r,n}(1+i)^{-n} \tag{37}$$

$$U_{r,n} = \frac{L}{Nd} + \left(L - \frac{L}{Nd}n\right) \times R_r \tag{38}$$

Where $U_{r,n}$ is the interest on the loan that must be paid in the nth year that the renewable energy plant has been operational; Nd is the amount of time that the financing for the renewable energy plant will be in effect; L is Total loans for renewable power plants; R_r is the interest rate on loans for renewable energy.

(4) Renewable energy tax costs:
Due to differences in tax and financial systems, domestic renewable energy costs need to take into account the 50% instant VAT rebate and the three exemptions and three halves of income tax.

$$T_r = \begin{cases} \sum_{n=1}^{N}(0.5T_{r,value} + T_{r,sales})(1+i)^{-n} & N \leq 3 \\ \sum_{n=1}^{N}[0.5(T_{r,value} + T_{r,incomes}) + T_{r,sales}](1+i)^{-n} & 3 < N \leq 6 \\ \sum_{n=1}^{N}(0.5T_{r,value} + T_{r,incomes} + T_{r,sales})(1+i)^{-n} & N > 6 \end{cases} \tag{39}$$

Where $T_{r,value}$ is Value Added Tax; $T_{r,sales}$ is Business taxes and surcharges; $T_{r,incomes}$ is Income tax of renewable energy.

(5) Renewable energy environment costs:

$$F_r = \sum_{n=0}^{N} F_{r,n}(1+i)^{-n} \tag{40}$$

Where $F_{r,n}$ is Carbon cost of thermal power in year n.

(6) Renewable energy depreciation tax credit:
Renewable energy units are depreciated by linear depreciation method.

$$V_r = \sum_{n=1}^{Nz} V_{r,n}(1+i)^{-n} \tag{41}$$

$$V_{r,n} = \frac{(1-VI)}{N} \times 100\% \tag{42}$$

Where $V_{r,n}$ is Tax credit for depreciation of Renewable energy units in year n; VI is the predicted final residual value rate of renewable energy units.

(7) Residual value of renewable energy:

$$G_r = G(1+i)^{-N} \tag{43}$$

Where G_r is Residual value of renewable energy.

(8) Renewable energy generation:

$$E_r = \sum_{n=1}^{N} E_{r,n}(1+i)^n \tag{44}$$

Where $E_{f,n}$ is Generation of Renewable energy in year n.

In summary, the Renewable energy LCOE calculation model is:

$$LCOE = \frac{I_r + R_r + T_r + S_r + F_r - V_r - G_r}{E_r} \tag{45}$$

6 Calculation Example Analysis

This paper selects post-combustion calcium desulphurisation thermal power units and wind turbines in a region of Liaoning Province for data analysis, where the carbon market price is adopted as the national average price of RMB55/tonne in the carbon trading market; the CCER price is adopted as the national average price of RMB30/tonne. The guidelines that govern the operation of the national carbon trading market stipulate that thermal power plants are permitted to invest up to five percent of their total carbon permits in the form of CCERs. The following is a rundown of the unit data:

Table 2 Thermal power unit data 1

Installed capacity (WM)	200 MW
Planned operating life (year)	25
Average annual hours of use	4000
Investment costs own funds (million yuan)	13856
Investment cost loan funding (million yuan)	55424
Loan Rates (%)	4.9%
Repayment period (year)	15
Repayment methods	Equal principal
Annual O&M costs (million yuan)	3120
Depreciable life for fixed assets (year)	15
Residual Value Rate (%)	5%
Annual depreciation charge (million yuan)	4100

Table 3 Thermal power unit data 2

Installed capacity (WM)	200 MW
Planned operating life (year)	25
Average annual hours of use	4000
Investment costs own funds (million yuan)	9653
Investment cost loan funding (million yuan)	46720
Loan Rates (%)	4.9%
Repayment period (year)	15
Repayment methods	Equal principal
Annual O&M costs (million yuan)	2700
Depreciable life for fixed assets (year)	15
Residual Value Rate (%)	5%
Annual depreciation charge (million yuan)	3520

Table 4 Renewable energy unit data 1

Installed capacity (WM)	50 MW
Planned operating life (year)	25
Average annual hours of use	1290
Investment costs own funds (million yuan)	8100.251
Investment cost loan funding (million yuan)	32980
Loan Rates (%)	4.9%
Repayment period (year)	15
Repayment methods	Equal principal
Annual O&M costs (million yuan)	220
Depreciable life for fixed assets (year)	15
Residual Value Rate (%)	5%
Annual depreciation charge (million yuan)	1092

Table 5 Renewable energy unit data 2

Installed capacity (WM)	50 MW
Planned operating life (year)	25
Average annual hours of use	1320
Investment costs own funds (million yuan)	8320.752
Investment cost loan funding (million yuan)	33283.008
Loan Rates (%)	4.9%
Repayment period (year)	15
Repayment methods	Equal principal
Annual O&M costs (million yuan)	240
Depreciable life for fixed assets (year)	15
Residual Value Rate (%)	5%
Annual depreciation charge (million yuan)	1195.77

Table 6 Renewable energy and thermal power LCOE calculation results

Costs/Type	Thermal Power 1	Thermal Power 2	Renewable Energy 1	Renewable Energy 2
No consideration of carbon costs	0.3622	0.3564	0.2216	0.2186
Consider the cost of carbon	0.3765	0.3691	0.209	0.2019
Benchmark/Guidance Tariffs	0.3749	0.3749	0.47	0.47
Rate of cost change after carbon cost pass-through	3.9%	3.5%	−5.6%	−7.6%

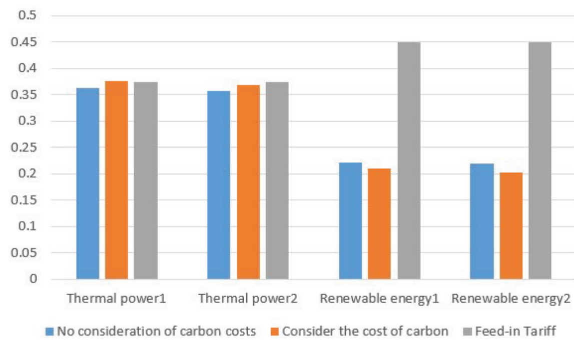

Figure 5 Project LCOE and feed-in tariff.

The feed-in tariff for new projects is implemented in accordance with the local benchmark price for coal-fired power generation, as stated in Development and Reform Electricity Price [2021] No. 833, "Notice on Matters Relating to the New Energy Feed-in Tariff Policy in 2021." Alternatively, the feed-in tariff can be formed voluntarily through participation in market-based transactions. In the geographic region where the unit that is the subject of this study is located, the benchmark price for coal-fired power generation is RMB0.3749/kWh.

Matlab software was used to derive the LCOEs for thermal and wind turbines with and without carbon emission cost transmission, respectively, and to compare them with the feed-in tariffs for thermal and renewable energy units in Liaoning Province.

When the cost of carbon emissions is factored in, the levelized cost of energy (LCOE) for both thermal power and renewable energy sources shifts, as is evident in Table 6 and Figure 5. The LCOE for the two renewable power plants decreased from RMB 0.2216/kWh to RMB0.209/kWh; and from RMB 0.2186/kWh to RMB 0.2019/kWh. The rate of decrease was 5.6% and 7.6% respectively. Since Liaoning province is in China's defined wind resource zone 4, the guideline feed-in tariff for renewable energy plants is RMB 0.47/kWh. after carbon market CCER earnings, the LCOE for renewable energy is well below the guideline feed-in tariff of RMB 0.47/kWh. This indicates that after taking into account the electricity market and the carbon market together and establishing the "electricity-carbon" market coupling synergy, renewable energy will gain more profitability. This will help to promote the market-oriented consumption of renewable energy in China and will also help to reduce the abandoned wind and light rates.

Similarly, as can be seen from the graph, the LCOE of thermal power rises from RMB 0.3622/kWh to RMB 0.3765/kWh, respectively, after taking into account the cost of allowances incurred by thermal power in the carbon market; the rates of increase are 3.9% and 3.5% respectively. As China's carbon allowance allocation system currently adopts a free allocation method, the increase in LCOE for thermal power is not significant after being affected by the cost of carbon emissions. However, the LCOE cost of one of the thermal units exceeded the benchmark feed-in tariff of RMB 0.3749/kWh in Liaoning Province, indicating that the profitability of thermal units will be further reduced after taking into account the "electricity-carbon" market linkage effect, and may even be reduced by the "electricity-carbon" price. This suggests that the profitability of thermal units will be further reduced, or even lose money due to the "electricity-carbon" market linkage. The cost of carbon from the carbon trading market will force thermal power plants to make a low-carbon transition or to provide ancillary services to wind power in order to obtain compensation for peaking, which will help China to achieve its "peak-carbon-neutral" goal.

7 Conclusion

The purpose of this paper is to present a carbon accounting framework for renewable energy and thermal power based on national regulations and the realistic operating characteristics of renewable energy and thermal power units. This framework takes into account the benefits of renewable energy in the carbon market as well as the costs of thermal power in the carbon market. The paper also proposes an LCOE calculation model based on the Gounod competitive carbon cost transmission principle, which is applicable to China's "electricity-carbon" market, and conducts a verification analysis based on two thermal power units and two wind power plants in Liaoning Province. The results show that the existing LCOE algorithm does not accurately reflect the exact costs of renewable energy and thermal power under the simultaneous construction of the electricity and carbon markets, and that the LCOE of both renewable energy and thermal power will be biased in this case, thus affecting their respective profitability.

The improved calculation method can be applied to the initial construction evaluation stage of renewable energy and thermal power. Since it takes carbon emission cost and China's tax policy into account, it can more accurately reflect the kilowatt-hour cost of the construction of power generation projects, which is conducive to the evaluation of the economy and investment return cycle of new power generation projects. At the same time, because the improved calculation method adopts the Cournot-Nash equilibrium carbon emission cost transmission model, the calculation process can integrate market supply, demand structure and competition degree and other factors, which can better reflect the regional differences in the construction process of power generation projects. It is helpful to evaluate the competitiveness and cost of new power generation projects in this region in the face of market competition from a regional perspective, so as to better assist the construction of new power generation projects.

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Biographies

Jian Zhang is a native of Anshan, Liaoning, Master (Power System and its Automation), Senior Engineer, State Grid Company Level Skill Expert, Deputy Director of Market Department of Liaoning Power Trading Center Co., Ltd. His main research interests are power market operation and management, power grid regulation and operation, with rich practical experience in power market construction and operation, power grid real-time operation, etc. He has in-depth research on medium and long term and spot market convergence, medium and long term continuous operation.

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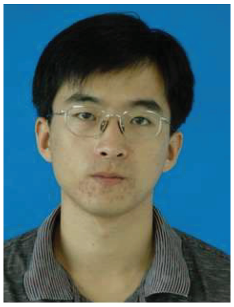

Xiaohe Liang is a master's student of Tianjin University, majoring in power system and its automation. In May 2018, she started to work in Liaoning Electric Power Trading Center Co. He is familiar with market-oriented trading business and participated in organizing the first batch of green power trading in China, with Liaoning leading the country in electricity turnover.

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Jipeng Kuai is the Deputy Director of Settlement Department of Liaoning Power Trading Center Co. He is mainly devoted to power trading settlement management and financial management, and is the builder of financial system of Liaoning power trading.

Nannan Xia has a Bachelor's degree in Accounting (CPA Specialization) from Liaoning University and a Master's degree in Accounting from Northeastern University of Finance and Economics, and has worked as an accountant in Liaoning Power Trading Center Co. He has in-depth research on internal control of power trading and is experienced in financial management and power trading settlement.