Research on the cost allocation mechanism of wind power heating in China from a cost-benefit perspective
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Abstract: Countries have formulated different transformation plans due to differences in resource endowments, energy strategies, and technological levels. Among them, the Chinese government has proposed continuing to increase the proportion of renewable energy generation in the field of power supply, especially the proportion of wind power, to achieve energy transition. Northern China is rich in wind energy resources, and the demand for heating in autumn and winter is high, providing favorable conditions for promoting wind power heating from the perspective of energy supply and demand. However, the costs and benefits of wind power heating for each participant greatly differ at various stages, and thus, it greatly affects their enthusiasm for participating in wind power heating projects, resulting in great difficulties in promoting and developing wind power heating. Therefore, this study takes Zhangjiakou, a pilot city of wind power heating in northern China, as an example to explore the cost allocation mechanism of wind power heating in China. First, the corresponding costs and benefits for the main participants in wind power heating are analyzed. Second, to consider the impact of the carbon emission reduction benefits and investment payback period on the cost allocation of wind power heating, four scenarios are constructed. Third, based on a cooperative game model, a new cost allocation design for the main participants is developed. Fourth, the key policy factors of the wind power heating trading mechanism and urban heating planning are analyzed. Finally, some suggestions for the promotion and sustainable development of wind power heating are proposed.

Keywords: renewable energy; cost allocation; cooperative game; allocation mechanism; wind power heating.

1. Introduction

The Chinese government attaches great importance to the development and utilization of renewable energy and has formulated corresponding industrial support policies and green recovery plans to accelerate the transformation of the energy structure to a low-carbon structure. Wind energy resources are abundant in northern China, and at the same time, the requirements for thermal comfort and environmental quality have become increasingly strong, so the energy consumption of heating systems in the future is bound to increase substantially, placing pressure on both the energy supply and the environment[1], making the promotion of wind power heating in northern China a potential solution to promote the development of low-carbon energy transformation. At present, there are two main heating methods in northern China: central heating through a city’s local heating station or a separate domestic stove burning bulk coal for home heating[2]. Under the traditional heating method, the incomplete combustion of coal releases many air pollutants. However, the use of clean energy can
effectively reduce air pollutant emissions and the associated health risks\textsuperscript{[3]}. Therefore, China is actively promoting clean energy power generation. Especially considering the "14th Five-Year Plan", the promotion of clean heating in northern China has become an important decision-making deployment mechanism proposed by the central government. In May 2022, the Ministry of Finance proposed expanding the scope of support for clean heating in winter in northern China and encouraging the use of clean energy for heating based on local conditions. The subsidy amount is determined according to the size of the city: 1 billion yuan per year for municipalities, 700 million yuan for capital cities, and 500 million yuan for prefecture-level cities\textsuperscript{[4]}. Compared with traditional heating methods, wind power heating, as a clean heating method in northern China, not only effectively alleviates environmental pollution but also promotes the clean utilization of energy by improving wind energy consumption. Among the cities in northern China, Zhangjiakou, which is a national-level renewable energy demonstration area with a ten thousand kilowatt wind power base in northern China and, in particular, a pilot area for wind power heating projects in the Beijing-Tianjin-Hebei region, is faced with the challenges of breaking through the bottleneck of traditional Chinese electricity trading subsidies, solving the problem of the abandonment of wind and light, and promoting clean heating. After investigation and analysis, it can be observed that in the current implementation of wind power heating projects, the costs and benefits of the participants involved greatly differ, and thus, the levels of enthusiasm of these participants are inconsistent. Especially after the improvement of the utilization rate of wind power, wind power generation companies are reluctant to supply power at a low price, and the government faces difficulty in providing sustainable economic subsidies, bringing about enormous problems for wind power heating. Therefore, building a multiparty cooperation mechanism suitable for areas that are rich in wind power and photovoltaics to promote the sustainable development of wind power heating is a common problem faced by Zhangjiakou as well as China as a whole.

However, under the current energy prices and policy conditions, the economy of electric energy substitution technology related to wind power heating is weak\textsuperscript{[5]}. Wind power heating is still in a trial operation stage, so the economy of carbon emission costs that lacks quantification makes it difficult to reflect the true value of such heating, making it less competitive than traditional heating. Therefore, the cost of wind power heating projects needs to be shared by the government, enterprises, and residents for coordinated advancement\textsuperscript{[6]}. The literature on wind power heating can be divided into the following categories:

- The first category of studies focuses on the environmental and health benefits brought about by wind power heating compared to traditional coal heating\textsuperscript{[7]}. Studies have found that air pollution in northern China has obvious seasonal characteristics. Compared with the nonheating period, two-thirds of the increase in air pollutants during the heating period is caused by coal-fired heating in winter. In addition, coal-fired heating aggravates environmental pollution and seriously affects people's health\textsuperscript{[8][10]}. Since the replacement of traditional heating with wind power heating, the concentration of PM2.5 during the heating season in the Beijing-Tianjin-Hebei region and surrounding areas has been significantly reduced\textsuperscript{[11]}, and the improvement in air quality has effectively increased the quality of life for urban residents\textsuperscript{[12]}.
- The second category of studies focuses on the economy of clean energy heating and its influencing factors rather than the economy of traditional energy heating. Considering the
technical performance of clean energy heating, some scholars have researched clean coal-
fired central, natural gas, electric, and other renewable energy clean heating

technologies\textsuperscript{[13]}\textsuperscript{[14]} and made an overall evaluation of the above clean heating technology
scheme in terms of indoor air temperature, energy-saving effect, and environmental impact\textsuperscript{[15]},

Another focus is the evaluation of the economy of wind power heating, as the problems faced
by such heating are important factors affecting its promotion\textsuperscript{[15]. Among these factors,
household economic level, labor price, local energy market development, and household
demographic characteristics have a particularly significant impact on people's willingness to
pay for clean heating \textsuperscript{[17]}\textsuperscript{[18]}\textsuperscript{[19]}.

- The third category of studies focuses on the implementation effect of clean heating policies,
including the effectiveness, cost, energy poverty, and energy inequality associated with clean
heating. In recent years, evaluation methods, such as regression discontinuity designs,
instrumental variables, propensity score matching, and difference-in-differences models,
have been widely used in policy evaluation \textsuperscript{[20]}\textsuperscript{[21]}. Some scholars have evaluated the effect
of the implementation quality of clean heating policies and found that clean heating policies
have significantly improved regional air quality \textsuperscript{[22]}\textsuperscript{[23]}. However, the change in the heating
method used increases the heating costs of residents and, to a certain extent, widens the gap
between rich and poor individuals\textsuperscript{[24]}\textsuperscript{[25]}.

Based on previous research, this study considers the environmental and health benefits of wind
power heating and, based on cooperative game theory, analyzes the income and expenditure of each
game party under a four-party cooperation mechanism. Then, the benefits of each participant
considering carbon emission reduction and the investment period in different scenarios are analyzed.
Finally, given the sustainability and reproducibility of this four-party cooperation mechanism,
suggestions for the optimization of the wind power heating price policy are proposed.

The rest of this paper is organized as follows. Section 2 analyses the potential costs and benefits
of the main participants. Section 3 introduces the research design of the cost allocation mechanism in
detail. Section 4 presents the results and discussions. Section 5 provides the conclusions and related
suggestions.

2. Potential costs and benefits of wind power heating

2.1 The environmental and health benefits of wind power heating

Wind-power heating can significantly reduce air pollution and, to a certain extent, improve
residents' quality of life and health. This paper takes the "Zero Carbon Winter Olympics", namely, the
Chongli District of Zhangjiakou, as a practical case to analyze the environmental and health benefits
of wind power heating.

At present, the Chongli District of Zhangjiakou uses large-scale coal-fired boilers for centralized
heating. There are two centralized coal-fired boiler heat source plants (heat source plant A and heat
source plant B), with a total heating area of 2.04 million square meters (1.428 million square meters
for ordinary residential buildings and 612,000 square meters for commercial and public buildings).
The ratio of residential buildings to public buildings is approximately 7:3. The annual heating period
is five months. Heat source plant A is equipped with two 56 MW assembled coal-fired boilers, covering an area of 19,113.43 square meters and a heating area of 880,000 square meters. Heat source plant B is equipped with three 46 MW coal-fired boilers, covering an area of 15,333.41 square meters and a heating area of 1.16 million square meters.

This paper uses the benefit-risk assessment health impact screening and mapping tool (CO-Benefits Risk Assessment (COBRA)) for environmental and health impact assessment. This tool can provide preliminary estimates of the impact of changes in air pollution emissions on ambient particulate matter air pollution concentrations, translate these estimates into health impacts, and then monetize these impacts. The measurement results show that Zhangjiakou's 2025 emission reductions of CO2, SO2, and NOx are 91,235 tons, 84 tons, and 82 tons, respectively, which correspond to environmental benefits of 31.17 Million USD, 1.25 million USD, and 3.51 million USD, totaling 35.93 million USD. Therefore, the economic benefit of carbon emission reduction in Zhangjiakou in 2025 is USD 45.94 million, of which the environmental benefit is USD 35.93 million and the health benefit is USD 10 million.

2.2 Potential costs and benefits for the main participants

Through investigation, it is found that the current policies related to clean heating have not effectively solved the problems faced in the implementation of electric heating projects in China. For example, an important problem faced by wind power heating projects in the Zhangjiakou area is that there are large differences between the cost inputs and benefits of each stage involved in wind power heating, as well as overall future benefits, and this has caused great differences in the levels of enthusiasm of parties to participate in wind power heating projects. Therefore, it is necessary to optimize the current policy system from the cost–benefit perspective to support the effective implementation of wind power heating projects. To this end, this study innovatively proposes a four-party cooperation mechanism based on the main participants of the wind power heating project.

As shown in Figure 1, the main participants in wind power heating include the government, power generation companies, power grid companies, and heating companies, and these comprise the framework of the four-party cooperation mechanism. The government has the responsibility and obligation to lead the four-party cooperation mechanism, providing financial subsidies and tax relief and promoting the energy transition and sustainable economic development. The power grid company upgrades and retrofits the power transmission grid to promote the development of regional power grids. With the increase in electricity consumption, it makes profits through power transmission and the distribution tariff to realize corporate strategy. When heating companies join the four-way cooperation mechanism, the main cost inputs are related to electric heating equipment, but wind power can be used instead of traditional energy sources to save heating costs. With the implementation of wind power heating, the power generation volume is increased, and the income of power generation companies will also increase. At the same time, wind power heating is conducive to encouraging power generation companies to carry out cross-industry cooperation. The four-party coordination mechanism for wind power heating can, to some extent, mitigate unwanted competition among the parties. It also enhances participant enthusiasm, facilitates efficient resource integration, and improves the interests of all parties by reducing costs.
Figure 1. Four-party cooperation mechanism for wind power heating

(1) Cost–benefit analysis of the government

First, the environmental and health benefits of wind power heating can reduce local government expenditures on medical and health care. Second, as the leader of wind power heating, the government provides financial subsidies, tax relief, and other types of policy support for wind power heating projects. Third, from the government’s perspective, wind power heating is not only related to the implementation of an energy transformation strategy but also an effective way to achieve carbon neutrality, the path of which is related more to environmental protection and sustainable development than to other factors. The cost–benefit analysis of the other three participants is shown below.

(2) Cost–benefit analysis of the power grid company

The costs faced by a power grid company include construction and operating costs. To meet the demand for wind power heating, the power grid company needs to rebuild and expand its substations of different voltage levels. The related construction costs include overall construction costs, equipment procurement costs, and installation engineering fees. The income of the power grid company includes the electricity revenues of electric heating and excess power generation, except that of electric heating power. We adopt the following formula to calculate the revenue of the power grid company:

\[ E_A = s_1 (h_1 - h_2) W_1 P_{s1} + (1 - s_1) (h_1 - h_2) W_1 P_{s2} + \left( (h_1 - h_2) W_1 - Q \right) (s_3 P_{m1} + (1 - s_3) P_{m2}) - \left( (h_1 - h_2) W_1 - Q \right) P_q \]  

where

- \( h_1 \): Wind power utilization hours
- \( h_2 \): Wind power guarantee acquisition hours
- \( W_1 \): Wind power grid connection
—$P_q$: Wind power mandatory settlement of electricity prices
—$s_1$: Proportion of valley electricity in power transmission and distribution
—$P_{s1}$: Valley power transmission and distribution price
—$P_{s2}$: General transmission and distribution price
—$s_2$: Resident heating power accounting for the proportion of total electric heating power
—$P_{g1}$: Residential electricity heating price
—$P_{g2}$: Industrial and commercial electricity heating price
—$s_3$: Residents' electricity remaining in addition to electricity and heating accounting for the proportion of total electricity, excluding electricity and heating
—$P_{m1}$: Resident electricity purchase price
—$P_{m2}$: Industrial and commercial power purchase price
—$Q$: Electric heating load power

(3) Cost–benefit analysis of the wind power company

The costs of a wind power company include construction and operating costs. Among them, construction costs include construction auxiliary engineering costs, equipment and installation engineering fees, construction costs, other engineering construction costs, and basic preliminary costs, while operating costs include labor wages and benefits, repair costs, material costs, insurance costs, and other expenses. The income of a wind power company includes power generation efficiency, heating income, and electricity price subsidies for heating. We calculate the revenue of the wind power company of residents with $E_B$ as follows:

$$E_B = (h_1 - h_2) W_1 (P_b + P_q)$$

where

—$P_b$: Clean energy subsidies

(4) Cost–benefit analysis of the heating company

The costs of a heating company include those related to the purchase of electric boilers, heat storage tanks, and other equipment and the upgrading of existing plant construction and heating pipe networks. Construction costs include overall construction costs, equipment procurement costs, and installation engineering fees. Operating costs include power costs (electricity costs for the operation of boilers and auxiliary equipment) and operation and maintenance costs (maintenance costs, wages and benefits, boiler periodic inspection fees, water rates, and other costs). The income of the heating company includes the heating fees paid by residents and industrial and commercial users. Calculated with each heating season being five months, heating costs are multiplied by the heating area and monthly heating costs. We adopt the following formula to calculate the revenue of the heating company:

$$E_C = 5s_2 MP_1 + S(1 - s_2) MP_2 - s_1 QP_{s1} + (1 - s_1) QP_{s2} + s_2 QP_{g1} + (1 - s_2) QP_{g2} + QP_z$$

where

—$M$: Wind power central heating area
—$P_1$: Monthly heating cost per unit area
$P_2$: Monthly cost of industrial and commercial heating per unit area

$P_z$: Government funds and surcharges

3. Research design

3.1 Cost and benefit allocation of clean heating in typical scenarios

(1) Scenario assumption

To reasonably calculate the benefits and costs of each party, this study uses scenario analysis to discuss multiple scenarios. Scenario analysis is an intuitive qualitative forecasting method that can predict possible situations under the premise that a certain phenomenon or trend continues. The key to scenario analysis is the selection of influencing factors, referring to those factors that affect the future development trend; the change in the status of influencing factors determines the future development trend and direction. The main considerations of the scenario design in this paper are carbon emission reduction, the investment period, and the operation period. The four scenarios are shown in Table 1.

<table>
<thead>
<tr>
<th>Scenario assumption</th>
<th>Main factors to consider</th>
<th>Carbon emissions</th>
<th>Investment period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline scenario</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Typical scenario I</td>
<td>X</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Typical scenario II</td>
<td>✓</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Typical scenario III</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

(2) Scenario description

1) **Baseline scenario**: Regardless of the investment period and level of carbon emission reduction, the benefits of wind power heating operations should be considered. All investments based on existing infrastructure or future investments are entirely borne by the government. This scenario is set up to calculate the benefit allocation without increasing investment.

2) **Typical scenario I**: Considering the investment period and ignoring carbon emission reduction, the grid company needs to consider the issue of investment funds from a market-oriented perspective, as all investments are undertaken by the grid company. This scenario calculates the possibility of independent investment by the grid company.

3) **Typical scenario II**: Regardless of the investment period and considering carbon emission reduction, the public promotes the development of wind power heating through its demand for
environmental improvement. The setting of this scenario is the calculation of the degree of improvement of the environmental benefits due to wind power heating.

4) Typical scenario III: Considering the investment period, carbon emission reduction, and economic and environmental benefits of participants, the government, public, and power grid companies should jointly participate. The setting of this scenario is the calculation of the feasibility of centralized and decentralized heating.

3.2 Cost allocation mechanism based on the cooperative game model

(1) Model assumption

A cooperative game is a game played by players in the form of alliance and cooperation to study the problem of income distribution when people achieve cooperation. Such a game can enhance the interests of both parties and the whole society. Moreover, cooperative games can produce a cooperative surplus. Based on the basic idea of a cooperative game, this study constructs a cooperative game model of wind power heating among the government, a grid company, a wind power company, and a heating company, the relevant assumptions of which are presented below.

The hypothesis of the bounded rationality of the game subject: the core of bounded rationality is the principle of satisfaction. During the decision-making process, the subject of the game formulates alternative options based on the limited information that he or she obtains and selects the most satisfactory option[30]. Governments need to lead participants in developing programs that are adapted to current economic and environmental developments. Grid companies, heating companies, and power producers need to consider mutual benefits to form a collective interest maximization.

The cost–benefit hypothesis of game participants: from the perspective of sustainable wind power consumption, only participants can continue to benefit from wind power heating, and thus, they continue to cooperate.

Market-oriented green power trading hypothesis: It is assumed that the amount of electricity outside the annual utilization hours of guaranteed purchases is used to participate in green power trading and settle at the market trading price.

(2) Model construction

During the operation stage of wind power heating, the grid company, wind power company, and heating company have certain economic benefits depending on whether they operate independently or jointly. When the total revenue of joint operations exceeds that of independent operations, the grid company, wind power company, and heating company choose to cooperate to maximize revenue. Therefore, the payoff function can be constructed under the condition of the independent action of participants, two-party cooperation, and three-party cooperation, and the optimal cooperation scheme can be identified by solving the payoff function. The model of such a cooperative game is constructed as follows:

① $S_{AB} = \{\text{Grid company, wind power company}\}$
Cooperation between the grid company and the wind power company allows for the installed capacity of wind farms to be fully connected to the grid with no wind curtailment. According to the provisions of the four-party cooperation mechanism, the excess power generation of the wind power company participating in trading is returned to allow the company to earn different incomes. However, the excess power generation that is not traded back does not provide the company with any additional income. The expression of cooperation income for the grid and wind power companies can be calculated using the following formula:

\[ E_{AB} = (1 - s_4) (h_1 - h_2) W_2 (s_3 P_{m1} + (1 - s_3) P_{m2}) + s_4 (h_1 - h_2) W_2 (s_3 P_{m1} + (1 - s_3) P_{m2} + P_a - P_q) + (h_1 - h_2) W_2 P_b + s_1 (h_1 - h_2) W_2 P_{s1} + (1 - s_1) (h_1 - h_2) W_2 P_{s2} + s_2 QP_{g1} + (1 - s_2) QP_{g2} \]

where

- \( s_4 \): Percentage of excess power generated by a wind power company that participates in the four-party collaborative transaction
- \( W_2 \): Wind power installation capacity
- \( P_a \): Benchmark feed-in tariff

\( S_{AC} = \{ \text{Power grid company, heating company} \} \)

In the cooperative alliance between the power grid and heating companies, the grid company can reduce wind power grid connection restrictions, increase regional wind power penetration, and sell more electricity to the heating company during periods of low power consumption, thus reducing the heating company's operating costs. The expression of cooperation income is as follows:

\[ E_{AC} = 5s_2 MP_1 + 5(1 - s_2) MP_2 + (h_1 - h_2) W_1 - Q) (s_3 P_{m1} + (1 - s_3) P_{m2} + (s_1 P_{s1} + (1 - s_1) P_{s2}) - P_q) - QP_z - s_2 QP_{g1} + (1 - s_2) QP_{g2} \]

\( S_{BC} = \{ \text{Wind power company, heating company} \} \)

Cooperation between the wind power and heating companies allows the two parties to purchase electricity directly, the heating company and wind power company to trade directly, and the on-grid electricity prices and transmission and distribution prices to be calculated separately. The income expression is as follows:

\[ E_{BC} = 5s_2 MP_1 + 5(1 - s_2) MP_2 - QP_z - QP_{s1} + (h_1 - h_2) W_1 (P_q + P_b) + (h_1 - h_2) W_1 - Q)P_q + (h_1 - h_2) W_1 P_b \]

\( S_{ABC} = \{ \text{Power grid company, wind power company, heating company} \} \)

For cooperation among the power grid, wind power, and heating companies, within the framework of the four-party cooperation mechanism, the wind power company can merge all abandoned wind power into the power grid to increase revenue, the power grid company can obtain more revenue from transmission and distribution, and the heating company can use low electricity prices to reduce operating costs. Hence, the income of the alliance includes the heating costs of the heating company, electricity income from excess electricity generation (including transmission and distribution costs), and electricity income from heating electricity, while costs include government funds and surcharges. The expression of the benefits of this cooperation among the three actors is as
follows:
\[ E_{ABC} = 5 s_2 M P_1 + 5(1 - s_2) M P_2 - Q P_4 + (h_1 - h_2) W_2 P_0 + (h_1 - h_2) W_2 - Q \ (s_3 P_{m1} + (1 - s_3) P_{m2}) + s_4 (h_1 - h_2) W_2 (P_0 - P_4) \]

(7)

(3) Model solution

According to Adams' fairness theory, if resources are allocated according to the contribution of team (alliance) members in the distribution of benefits, then the team's output level and members' cooperation enthusiasm can be improved\(^{[31]}\). The Shapley value is an important single-valued solution to cooperative games, and it can amortize costs or benefits according to marginal costs, with each member’s benefit being equal to its expected marginal contribution value of all alliances\(^{[32]}\). We adopt the Shapley method to calculate the game model as follows:

\[ X_i(v) = \frac{(|S| - 1)! \ (n - |S|)!}{n!} \left[ V(S) - V(S - \{i\}) \right] \]

(8)

where

—\(V\): Characteristic function corresponding to each alliance in \(N\)

—\(V(S)\): Maximum profit that can be obtained if the players in alliance \(S\) cooperate

—\(|S|\): Number of elements in the set

—\(V(S - \{i\})\): Payoff if a company does not join the set

—\(\frac{(|S| - 1)! \ (n - |S|)!}{n!}\): Weighting factor

(4) Model data

According to the three-stage plan of clean heating, we calculate the benefits, costs, and distribution of each stage separately under the "four-party coordination mechanism" in Zhangjiakou.

1) First stage

In the first stage, there are three main planning parameters: heating area of 3.2 million square meters, installed wind power capacity of 10.94 million kilowatts, and power grid investment of 42.37 million dollars. According to the Beijing-Tianjin-Hebei Region Green Power Market Trading Rules, the incomes of the power grid, wind power, and heating companies in terms of electric heating are shown in Table 2.

Table 2. Cooperative game relations and benefits

<table>
<thead>
<tr>
<th>Cooperative game</th>
<th>Benefits</th>
<th>Spending</th>
<th>Earnings value (million dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power grid company A</td>
<td>Capital pool, electric heating, electricity sale,</td>
<td>Mandatory prices for heating electricity</td>
<td>759.08</td>
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</table>
Table 3. Detailed parameters of the three-stage plan for wind power heating

<table>
<thead>
<tr>
<th>Parameters and results</th>
<th>First stage</th>
<th>Second stage</th>
<th>Third stage</th>
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</thead>
<tbody>
<tr>
<td>Main planning parameters</td>
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<tr>
<td>Power grid investment (million dollars)</td>
<td>42.37</td>
<td>185.88</td>
<td>371.76</td>
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<tr>
<td>Wind power capacity (million kilowatts)</td>
<td>10.94</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Heating area (million square meters)</td>
<td>3.2</td>
<td>9.2</td>
<td>18.2</td>
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<tr>
<td>Annual income</td>
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<tr>
<td>Grid company (million dollars)</td>
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<tr>
<td>Wind power company (million dollars)</td>
<td>10.71</td>
<td>29.86</td>
<td>5906.93</td>
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<td>Heating company (million dollars)</td>
<td>53.18</td>
<td>68.61</td>
<td>86.11</td>
</tr>
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</table>

2) Second stage
In the second stage, according to the Beijing-Tianjin-Hebei Region Green Power Market Trading Rules, there are three main planning parameters: heating area of 9.2 million square meters, wind power installed capacity of 13 million kilowatts, and power grid investment of 185.88 million dollars.

3) Third stage
In the third stage, according to the Beijing-Tianjin-Hebei Region Green Power Market Trading Rules, there are three main planning parameters: heating area of 18.2 million square meters, wind power installed capacity of 15 million kilowatts, and power grid investment of 371.76 million dollars.

4 Results and discussion

4.1 Calculation results

(1) Calculation for the baseline scenario

1) First stage
The Shapley value formula is used to calculate the above game situations, and the income allocation statuses of grid company A, wind power company B, and heating company C are shown in Tables 4, 5, and 6, respectively.

### Table 4. The calculation process of the income distribution of the power grid company

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>A</th>
<th>A ∪ B</th>
<th>A ∪ C</th>
<th>A ∪ BC</th>
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<tr>
<td>v(S)</td>
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<tr>
<td>v(S\N)</td>
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<td>0.00</td>
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<tr>
<td>v(S) — v(S\N)</td>
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<td>0.00</td>
<td>759.08</td>
<td>759.08</td>
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<td>[S]</td>
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<td>2.00</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>w([S])</td>
<td>0.33</td>
<td>0.17</td>
<td>0.17</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>w([S]) [v(S) — v(S\N)]</td>
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<td>0.00</td>
<td>12.61</td>
<td>25.23</td>
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<td>φ_A(v)</td>
<td>37.84</td>
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### Table 5. The calculation process of the income distribution of the wind power enterprise

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>B</th>
<th>A ∪ B</th>
<th>B ∪ C</th>
<th>A ∪ B ∪ C</th>
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</thead>
<tbody>
<tr>
<td>v(S)</td>
<td>0.00</td>
<td>0.00</td>
<td>26.05</td>
<td>101.75</td>
<td></td>
</tr>
<tr>
<td>v(S\N)</td>
<td>0.00</td>
<td>0.00</td>
<td>56.26</td>
<td>80.32</td>
<td></td>
</tr>
<tr>
<td>v(S) — v(S\N)</td>
<td>0.00</td>
<td>0.00</td>
<td>21.42</td>
<td>21.42</td>
<td></td>
</tr>
<tr>
<td>[S]</td>
<td>1.00</td>
<td>2.00</td>
<td>2.00</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>w([S])</td>
<td>0.33</td>
<td>0.17</td>
<td>0.17</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>w([S]) [v(S) — v(S\N)]</td>
<td>0.00</td>
<td>0.00</td>
<td>35.70</td>
<td>71.40</td>
<td></td>
</tr>
<tr>
<td>φ_B(v)</td>
<td>107.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. The calculation process of the profit distribution of the heating enterprise

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>C</th>
<th>A ∪ B</th>
<th>B ∪ C</th>
<th>A ∪ B ∪ C</th>
</tr>
</thead>
<tbody>
<tr>
<td>v(S)</td>
<td>56.26</td>
<td>80.32</td>
<td>26.05</td>
<td>101.75</td>
<td></td>
</tr>
<tr>
<td>v(S\N)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>v(S) — v(S\N)</td>
<td>56.26</td>
<td>80.32</td>
<td>26.05</td>
<td>101.75</td>
<td></td>
</tr>
<tr>
<td>[S]</td>
<td>1.00</td>
<td>2.00</td>
<td>2.00</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>w([S])</td>
<td>0.33</td>
<td>0.17</td>
<td>0.17</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>w([S]) [v(S) — v(S\N)]</td>
<td>15.42</td>
<td>13.39</td>
<td>4.34</td>
<td>3391.06</td>
<td></td>
</tr>
<tr>
<td>φ_C(v)</td>
<td>53.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the above calculation results, it can be observed that in the first stage, the annual distributable incomes of the power grid, wind power, and heating companies are **37.84**, **107.1**, and **53.18 million dollars**, respectively, and this is quite different from the actual operating conditions of the green power market. The reason for this is that the construction of the cooperative game alliance centers on the development of wind power heating and that the heating company can obtain the most profit allocation.

2) Second stage
Using the Shapley value solution formula to calculate the above situation, the annual distributable incomes of the grid, wind power, and heating companies in the second phase are $24.50, $29.86, and $68.61 million dollars, respectively.

3) Third stage

Using the Shapley value solution formula to calculate the above situation, the annual distributable incomes of the grid, wind power, and heating companies in the third stage are found to be -$1.13, $5906.93, and $86.11 million dollars, respectively. We can see that the main problem at this stage is that the rapid increase in the area of electric heating causes grid companies to sell electricity at low prices and purchase electricity at high prices, thus losing money.

The analysis of the benefits of the three stages shows that the "four-party cooperation mechanism" of wind power heating is an effective development model. The increase in the revenue of wind power and heating companies is conducive to the implementation and development of wind power heating. However, with the increase in the size of the heating area, the grid company must undertake excessive heating power compensation, resulting in revenue reduction.

(2) Calculation for typical scenarios

1) Typical scenario I

Under the guidance of the current three-phase planning policy for clean heating, the implementation of central heating transformation requires $42.37, $185.88, and $371.76 million dollars, respectively, for a total of $0.6 million dollars, from the power grid, wind power, and heating companies. If the "coal-to-electricity" transformation is carried out at the same time, then each stage requires $0.17, $0.23, and $0.72 million dollars, totaling $1.11 million dollars, and the total investment in clean heating reaches $1.71 million dollars. In contrast, the “coal-to-electricity” grid construction plan included in the 13th Five-Year Plan provides only $92.92 million dollars. Therefore, the development of clean heating with the power grid company as the core faces major challenges.

In terms of central heating, the power grid company has invested $0.6 million dollars, but there is no corresponding investment in the 13th Five-Year Plan. According to the calculation of the baseline scenario, in the three stages, the power grid company has accumulated revenue of $0.32 million dollars, but there is still an investment gap of $0.28 million dollars. Due to losses in the three stages, it is difficult to recover the investment in the power grid, and central heating cannot be carried out on a large scale under the current rules. In terms of decentralized heating, the investment of the power grid company needs to reach $1.11 million dollars. Assuming 100% user utilization in the heating season, the electricity fee income is estimated to be $0.68 million dollars. Thus, in such a situation, the power grid company would lose $0.43 million dollars when only investment is considered, and therefore, the "coal-to-electricity" project would not be economical.

2) Typical scenario II

This study uses the benefit-risk assessment health impact screening and mapping tool (COBRA) for environmental and health impact assessment. According to the calculation results of COBRA, the economic benefit of carbon emission reduction in the Zhangjiakou area by 2025 is expected to be $45.93 million dollars, of which the environmental and health benefits are expected to be $35.93 and $10.01 million dollars, respectively. The government can subsidize or introduce a third party in which to invest
based on these factors. If cooperation can be reached, then the proceeds can be included in the alliance income. If the dominant position of the grid company is maintained and subsidized to the grid company, then the grid company's income will reach 43.12 million dollars in 2022-2025 and beyond.

3) Typical scenario III

This scenario involves the joint participation of the government, the public, and the power grid company and comprehensively considers the economic and environmental benefits of participants. In this scenario, the construction cost of the power grid and the economic benefit of carbon emission reduction during the investment period of the wind power heating project in 2025 are calculated, and cost–benefit allocation is carried out.

The cumulative income of the three stages of the recalculation of the grid company is 508.76 million dollars, but there is still a funding gap of 91.15 million dollars. However, after the third stage, the income of the power grid company is positive. Furthermore, after 2.09 years, grid investment can be recovered, exhibiting good economic efficiency.

4.2 Analysis of policy factors

Constrained by policy, the mandatory settlement electricity price is determined by the green power market transaction rules, and the wind power heating area is formulated by the policy plan. Gradually adjusting the mandatory settlement electricity price to effectively improve the feasibility of clean heating and, considering the coordinated development of the clean heating area and clean energy, in addition to determining the economic heating scale are important topics discussed in this study.

(1) Analysis based on the mandatory settlement electricity price

In wind power heating, the reduction in the mandatory settlement price effectively improves the profitability of the power grid company. The third stage of the benchmark scenario is analyzed to obtain the returns of the power grid and wind power companies under different variation ranges, as shown in Table 7.

<table>
<thead>
<tr>
<th>Price range</th>
<th>Price (dollars/MWh)</th>
<th>Income (million dollars)</th>
<th>Earnings (million dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>4.06</td>
<td>-2.27</td>
<td>118.14</td>
</tr>
<tr>
<td>-5%</td>
<td>3.85</td>
<td>7.64</td>
<td>112.23</td>
</tr>
<tr>
<td>-10%</td>
<td>3.65</td>
<td>17.54</td>
<td>106.32</td>
</tr>
<tr>
<td>-15%</td>
<td>3.44</td>
<td>27.44</td>
<td>100.42</td>
</tr>
<tr>
<td>-20%</td>
<td>3.25</td>
<td>37.35</td>
<td>94.51</td>
</tr>
<tr>
<td>-25%</td>
<td>3.03</td>
<td>47.25</td>
<td>88.60</td>
</tr>
<tr>
<td>-30%</td>
<td>2.84</td>
<td>57.16</td>
<td>82.70</td>
</tr>
<tr>
<td>-35%</td>
<td>2.64</td>
<td>67.06</td>
<td>76.79</td>
</tr>
<tr>
<td>-40%</td>
<td>2.43</td>
<td>76.96</td>
<td>70.88</td>
</tr>
</tbody>
</table>
It can be seen from the results that when the mandatory settlement electricity price is reduced by 5%, the grid company can have a positive income. Moreover, when the mandatory settlement electricity price is reduced by 10%, the revenue of the power grid company reaches 17.54 million dollars. Therefore, the payback period of the investment of the grid company is 13.04 years, which is economically viable.

(2) Analysis based on the heating area

An analysis of the third stage of the benchmark scenario allows the sensitivity analysis results to be obtained for the power grid and wind power companies under different heating area changes, as shown in Table 8.

<table>
<thead>
<tr>
<th>Heating area change range</th>
<th>Heating area (million square meters)</th>
<th>Grid company revenue (million dollars)</th>
<th>Wind power enterprise income (million dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>1,820</td>
<td>-2.27</td>
<td>118.14</td>
</tr>
<tr>
<td>-5%</td>
<td>1,729</td>
<td>0.65</td>
<td>112.23</td>
</tr>
<tr>
<td>-10%</td>
<td>1,638</td>
<td>3.56</td>
<td>106.32</td>
</tr>
<tr>
<td>-15%</td>
<td>1,547</td>
<td>6.48</td>
<td>100.42</td>
</tr>
<tr>
<td>-20%</td>
<td>1,456</td>
<td>9.39</td>
<td>94.51</td>
</tr>
<tr>
<td>-25%</td>
<td>1,365</td>
<td>12.31</td>
<td>88.60</td>
</tr>
<tr>
<td>-30%</td>
<td>1,274</td>
<td>15.23</td>
<td>82.70</td>
</tr>
<tr>
<td>-35%</td>
<td>1,183</td>
<td>18.14</td>
<td>76.79</td>
</tr>
<tr>
<td>-40%</td>
<td>1,092</td>
<td>21.06</td>
<td>70.88</td>
</tr>
</tbody>
</table>

It can be seen from the results that when the planned size of the heating area is reduced by 5% (that is, the heating area becomes 17.29 million square meters), the grid company can make a profit. However, to realize the sustainability of the investment of the power grid company, the heating area must be reduced by 35%. Hence, the income of the power grid company is 18.14 million dollars, which is economically viable.

Comparing the baseline scenario with typical scenario III and accounting for the economic benefits of carbon emission reduction, the total revenue of the wind power heating cooperative alliance is shown to increase by 45.93 million dollars. If these benefits are used to subsidize the loss of power grid construction and wind power heating, then clean heating can be made feasible, and grid investment can be quickly recovered. Most of the current obstacles to the implementation of wind power heating come from the heating company itself. When the benefits of wind power heating are weak, the heating company uses coal-fired heating instead. If these benefits can partially subsidize the heating company, then the scenario in which the economic benefit of carbon emission reduction is considered compensates for, to the greatest extent, the heating company.
4.3 Discussion

The analysis of the four scenarios of clean heating cost allocation shows that clean wind power heating affects all aspects of the interests of the government, power grid companies, power generation companies, and heating companies, namely, prices, the area setting for clean heating, and the distribution of carbon benefits.

(1) Mandatory Settlement Electricity Price and the Electricity Market

This area has established the Beijing-Tianjin-Tangshan green power market with wind power trading as the main body. There are two settlement mechanisms for electricity price settlement in the market: the market price and compulsory settlement of electricity price. From the perspective of economic calculation, if the market transaction price is used, the price will further decrease until it falls to 3.64 dollars/MWh for clean heating. The current compulsory settlement electricity price is 5.08 dollars/MWh. Comparing the current compulsory settlement electricity price and market price, market participants will choose the compulsory settlement electricity price based on their interests, leading to market failure. Adopting a dynamic forced settlement electricity price is a feasible solution. Market regulators or the government can adjust the forced settlement electricity price to be equal to or lower than the market value based on the expected market price and encourage wind and solar power plants to participate in market transactions and ultimately transition to a complete market transaction model.

(2) Generalizability of Heating Ranges

In the four-party cooperation mechanism, the power grid company is responsible for promoting clean heating throughout Zhangjiakou. As the government requires a rapid expansion of large-scale clean heating, more curtailment of wind and electricity will be needed in the next three years. However, from the perspective of the planned wind and solar power plants, the amount of wind and photovoltaic power generation in Zhangjiakou in the future will not be sufficient to support clean heating in the whole area, and the planned heating area will need to be reduced by 10% to 30%. The Zhangjiakou government or power grid company should plan clean heating based on the amount of abandoned wind and photovoltaic power to ensure the feasibility of clean heating. If the government provides subsidies for clean heating, it will also be necessary to clarify the subsidy amount from the perspective of an economic analysis of clean heating or introduce third-party investors to ensure that the investment mechanism for clean heating is feasible. As a national-level renewable energy demonstration area, Zhangjiakou has a strong demonstration effect. In Western China, there are many similar areas rich in wind and solar resources. If the government can coordinate the construction of wind and solar power plants with clean heating, this kind of multiparty joint promotion of clean heating will have a strong promoting effect.

(3) Interaction between the electricity market and the carbon market

Cleaner heating can reduce carbon emissions and improve air quality. By promoting clean heating on a large scale, the whole society can enjoy the benefits of green electricity and emission reduction. However, electricity trading in the green electricity market does not include the value of carbon emission rights; that is, beneficiaries do not pay. Based on the analysis of several typical scenarios, without considering the carbon emission benefits, the multiparty synergy mechanism of clean heating is not sufficiently economical and has no promotion value. Scenarios 2 and 3 consider the benefits of clean heating carbon emissions, and the economic benefits will be significantly improved; thus, this
constitutes the basis for improving and promoting the future quadrilateral cooperation mechanism.

Considering the value of carbon emissions, the interaction of the carbon market, green certificate market, and electricity market should be considered. Green certificate trading and carbon trading take place at the power generation end and the power consumption end of the grid, respectively, and power trading is the link between the two, connecting power generation and power consumption with electricity trading as a carrier. From the perspective of the formation mechanism of the carbon market, green certificate, and electricity market, the carbon market is policy-driven, and the market requires the government's mandatory emission restrictions on enterprises, while electricity trading is a demand-driven market, and the demand for electricity trading forms the electricity trading market. Considering the feasibility of clean heating participants to obtain benefits and the design of the three markets, it is necessary to design a reasonable market access mechanism so that clean heating entities can participate in the three markets. Furthermore, the government needs to reasonably allocate clean heating. The participation quota of the main body ensures the overall economy of clean heating.

5. Conclusion and Policy Implications

Wind power or solar power for the provision of clean heating is an important measure for reducing carbon emissions that the Chinese government has vigorously used in the northern region of the country in recent years. It is expected to improve air quality and promote the realization of the dual carbon goal. The rapid expansion of clean heating areas has raised the issue of sharing the interests of all parties involved, and economics has also become the core of whether the Chinese government can successfully meet its ambitious goals. Taking the Zhangjiakou national renewable energy demonstration area as an example, this study finds that the green electricity market transaction price, heating area setting, and distribution of carbon emission income are the key factors in achieving sustainable development. Based on the current policy conditions, carrying out clean heating in the Zhangjiakou area is not sustainable. Therefore, this research innovatively constructs a multiparty cooperation mechanism based on a cooperative game, realizes the sharing of costs and benefits, and urges all parties to reasonably share the costs and benefits.

Given the sustainable development of clean heating in China in the future, this study conducts an in-depth analysis of mandatory settlement electricity prices, the electricity market, the generalizability of the heating range, and the interaction between the electricity market and the carbon market. It makes the following suggestions:

(1) It is important to improve the transaction price settlement mechanism in the current green electricity market and adopt a dynamic mandatory settlement of electricity prices. At present, many provincial-level regions, such as Inner Mongolia, Shanxi, and Hebei, have conducted green power market transactions in China. Market regulators or the governments in each region can adjust the mandatory settlement electricity price to be equal to or lower than the market value based on the expected market price and encourage wind and solar power plants to participate in market transactions and ultimately transition to a full market transaction mode.

(2) The construction of wind and solar power plants and the coordinated planning of clean heating will improve the clean heating economy in areas in China with wind power and photovoltaic resources. China has many wind power and photovoltaic resources in the western regions, such as Guizhou,
Qinghai, and Inner Mongolia. The promotion of clean heating in these regions needs to consider the impact of different clean heating areas on the earnings of wind power companies, heating companies, and power grid companies. When setting the clean heating area in these regions, it is necessary to comprehensively plan the wind power heating area and the coordinated development of wind power and photovoltaic energy to determine the most economical wind power heating scale.

(3) It is important to effectively carry out the overall planning and coordinated development of the carbon emission rights market, green certificate market, and power market to ensure the sustainable development of clean heating. The role of the market mechanism in energy resource allocation and climate governance should be maximized. The large-scale development of renewable energy should be promoted. The top-level design of the three markets should be accounted for. The economics of clean heating entities should be fully considered. It is necessary to design reasonable market access so that the market mechanism allows the main body of clean heating to participate in the three markets. Furthermore, the government needs to reasonably allocate the participation quota of the main body of clean heating to ensure the overall economic and sustainable development of clean heating.

Data availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References


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