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Optimum Subsidy to Promote Electric Boiler Investment to Accommodate Wind Power

Da Liu [1,*], Shou-Kai Wang [1], Jin-Chen Liu [1], Han Huang [1], Xing-Ping Zhang [1], Yi Feng [2] and Wei-Jun Wang [1]

1 Beijing Key Laboratory of New Energy and Low-Carbon Development, North China Electric Power University, Beijing 102206, China; wsk425670241@ncepu.edu.cn (S.-K.W.); 1111570113@ncepu.edu.cn (J.-C.L.); 50601651@ncepu.edu.cn (H.H.); zxp@ncepu.edu.cn (X.-P.Z.); wwjhd@ncepu.edu.cn (W.-J.W.)

2 State Grid Electric Vehicle Service Co., Beijing 100053, China; fengyi@evs.sgcc.com.cn

* Correspondence: liuda@ncepu.edu.cn; Tel.: +86-10-6177-3138

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Abstract: The increasing development of combined heat and power (CHP) plants is exacerbating the wind power curtailment problem in regional power grids during the winter heating season. Electric boilers (EBs) were proposed to be employed within CHP plants to relieve this problem. However, CHP plants usually have no incentive for investing in EBs. Therefore, CHP plants must be incentivized to make such investments through appropriate compensation from beneficiaries, i.e., government and wind farms, although this has not previously been discussed. We propose a game theory model to simulate the impact of government subsidies on EB investment. We analyzed the utilization of the involved parties with the marginal cost and average cost and applied game theory to simulate the investment decisions. Then, an approximate enumeration technique was developed to identify the optimum government subsidy. An actual case of a regional power grid in northern China was investigated to validate the proposed method. A minimum government subsidy to maximize total social benefit was calculated; this subsidy can incentivize wind farms and CHP plants to invest in and use EBs.

Keywords: wind power accommodation; combined heat and power (CHP) plants; electric boilers (EBs); government subsidy; game analysis model

1. Introduction

Worldwide, wind power has become one of the most competitive renewable energies for mitigating energy and environmental problems despite its random and intermittent characteristics [1]. The rapid expansion of wind power over the past several years has evoked significant concern about the safety of its integration with the grid [2,3]. The problem is exacerbated in regional power grids, where combined heat and power (CHP) plants provide the majority of the electric power supply during the heating season. The development of CHP plants is encouraged through fixed feed-in tariffs and priority scheduling. Thence, the peak regulation capability of the power grid is abated by the CHP units' inflexible response during the heating season [4,5]. Massive wind power curtailment occurs and slows the worldwide effort to increase sustainable energy development [6]. Thus, an efficient method for mitigating wind power curtailment is urgently needed [7,8].

The majority of previous studies focused on energy storage technologies, demand response, interregional accommodation, and electric boilers (EBs). Energy storage is considered to be an effective method, and its technology has significant potential for improvement [9–11]. Demand response adjusts the load demand to match the variable wind power [12,13], whereas interregional accommodation is proposed to accommodate wind energy located far from the load center [14,15].

The use of EBs within CHP plants is suggested to increase the plant's power supply flexibility and improve the grid's capacity to accommodate wind power [16–18]. The electricity consumed by EBs reserves more grid capacity to accommodate wind power [16]. Employing EBs to accommodate wind power has been shown to be feasible using value analysis [19,20], scheme design [21,22], and optimal capacity allocation [16].

Investing in EBs will accommodate a larger amount of wind power, increase clean energy generation, and create additional wind farm profits. Therefore, both the government and wind farms are motivated to increase investments in EBs. From the perspective of social cost minimization, the installation of EBs in CHP plants via the cooperation of CHP plants is crucial. However, increasing the use of EBs decreases the profits of CHP plants by reducing their power output. CHP plants will reject the use of EBs unless sufficient compensation is provided by the government and wind farms.

Benefit allocation is important for projects in which multiple investors compete for advantageous positions and every investor strives to maximize profits with an optimum decision [23]. To address the conflicts that arise among the involved parties, a well-designed government subsidy scheme can reduce these conflicts and promote the implementation of these projects.

Subsidy policies have been extensively implemented to promote new energy development [24,25]. The government will face a trade-off in this type of project: achieving maximum social benefit subsidies while minimizing the total subsidy. However, no studies have addressed the impact of government subsidies on EB investments. In this paper, we aim to build a model to promote wind power accommodation with EB investment to maximize social benefits while minimizing the government subsidy.

The remainder of this paper consists of three sections: Section 2 discusses the background knowledge for employing EBs in CHP plants and the game model between wind farms and CHP plants for EB investment. Section 3 presents a case study of the Beijing–Tianjin–Hebei (BTH) power grid located in northern China to illustrate the proposed model. Section 4 presents the conclusion

2. Principles and Method

2.1. Background for Employing EBs in CHP Plants

We assume that EBs are installed in CHP plants and only run when wind power curtailment occurs [16]. In addition, all electricity consumed by the EBs is assumed to originate from the CHP units. With the supplementary heat generated by the EBs, the CHP units have additional capacity to respond to the regulation of the grid. The increase in the wind power accommodation of this system is equal to the decrease in the power supply of the CHP plant. Figure 1 shows the change in the electricity and heat production of the CHP plants after EBs are employed.

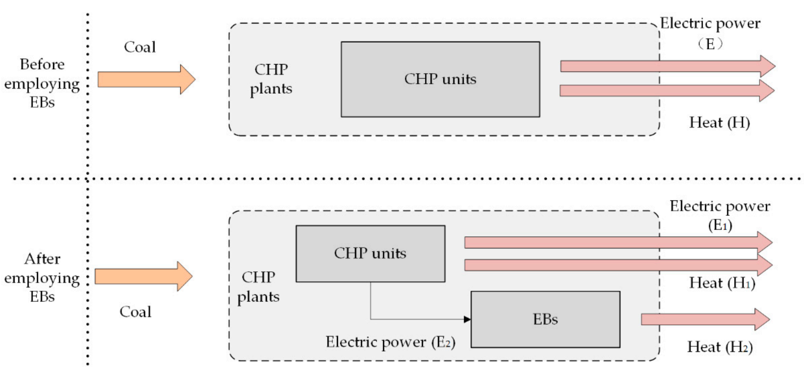

Figure 1. Change in the production of the CHP plant after employing EBs.

In the figure, E and H are the electric power supply (kW) and heat supply (GJ/h) from the CHP plants before employing EBs, respectively; E_1 and H_1 are the electric power supply and heat supply from the CHP units after employing EBs, respectively; and E_2 and H_2 are the power consumption of the EBs and the heat supply of the EBs, respectively.

Before employing the EBs, the CHP units generate electric power (E) and heat (H) by burning coal; after employing the EBs, the CHP units generate electric power ($E_1 + E_2$) and heat (H_1), whereas the EBs consume electric power (E_2) and provide heat (H_2). By employing EBs, the CHP plants provide electric power (E_1) and heat ($H_1 + H_2$).

We assume that the use of EBs does not change the total heat supply of the CHP plants as the EBs provide the exact amount of heat that was originally provided by the CHP units, as shown in Formula (1). For simplicity, the average thermoelectric ratio of all CHP units is assumed to be the same constant value before and after EBs are employed [16], as shown in Formula (2).

$$H = H_1 + H_2 \tag{1}$$

$$\frac{H}{E} = \frac{H_1}{E_1 + E_2} \tag{2}$$

After employing EBs, the gap in the electricity supply from the CHP plants, which is represented by $(E - E_1)$, is provided by wind power; this value is the wind power accommodation that would otherwise be curtailed. The effectiveness of employing EBs for wind power accommodation is calculated as

$$\theta = \frac{E - E_1}{E_2} \tag{3}$$

Thus, the quantity of wind power accommodation after employing EBs is

$$Q = \Delta t \times \sum_{t=1}^{T} (P_{W_t} \times v + P_B \times \theta \times (1 - V)) \tag{4}$$

$$v = \begin{cases} 0, & P_{W_t} \geq P_B \times \theta \\ 1, & P_{W_t} < P_B \times \theta \end{cases} \tag{5}$$

2.2. *Game Analysis Model*

2.2.1. Three-Sided Game Analysis for EB Investment

The interaction among three stakeholders (i.e., government, wind farms, and CHP plants) is analyzed in the framework of game. For simplicity, all wind farms and the CHP plants are considered to be one player. In the game model, we use Player G, Player W, and Player C to represent the government, wind farm, and CHP plant stakeholders, respectively. The social benefit of Player G—i.e., emissions reduction due to wind power accommodation—and the economic benefits of Player W and Player C are referred to the utilization in the game model.

The capacities of the EBs impact the utilization of the players by affecting the accommodated quantity of wind power. The three players try to maximize their utilization by adjusting their investment involvement, which determines the capacity of the EB installation. Player G provides a subsidy for EB investment. Player W provides a subsidy for EB investment and a profit concession to Player C for extra wind power sales. Player C invests in EB while enjoying subsidy and profit concessions from his counterparts. Thus, Player C serves a main role in the investment process; the actions of the three stakeholders are dependent on the decisions of Player C. The game flow is shown in Figure 2, and the process is detailed as follows:

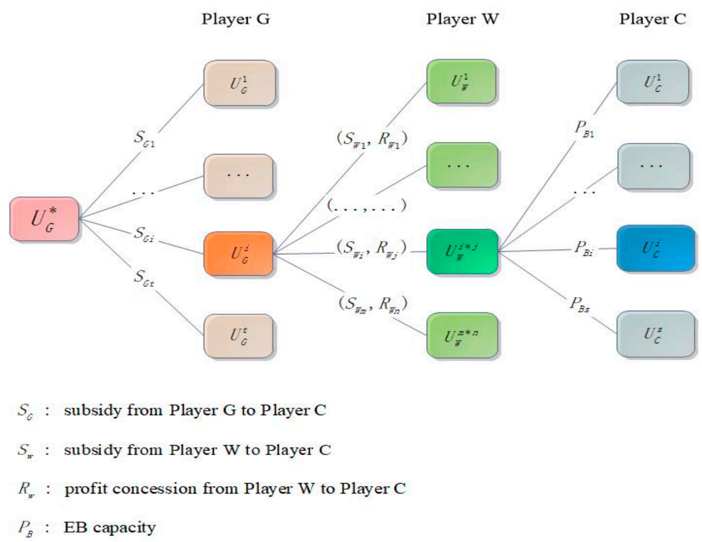

Figure 2. Game model flow process.

Step 1. Player G offers a set of subsidies to Player C, {S_{G1}, S_{G2}, ... , S_{Gt}}.

Step 2. Player W offers a set of subsidies {S_{W1}, S_{W2}, ... , S_{Wm}} and a set of profit concessions {R_{W1}, R_{W2}, ... , R_{Wn}} to Player C for a certain subsidy from Player G to Player C.

Step 3. Player C maximizes his utilization U_C by adjusting the installed EB capacity investment P_B in every scenario of {S_{Gi}, S_{Wj}, R_{Wk}}. The dominant strategy for Player C for each scenario is obtained.

Step 4. Player W determines his optimum strategy with minimum subsidies and profit concessions to maximum his utilization by comparing all strategies of Player C for every scenario.

Step 5. Player G determines his optimum strategy with minimum subsidies and maximum utilization by comparing all the strategies of Player W for every scenario.

The game model is shown in Formula (6).

$$z_3 = \max(U_G)$$
$$\text{s.t.}\begin{cases} z_2 = \max(U_W) \\ s.t.\begin{cases} z_1 = \max(U_C) \\ s.t.\{U_C > 0 \end{cases} \end{cases} \tag{6}$$

2.2.2. Utilization Analysis

The annual benefits and annual amortized costs of the initial investments that were calculated using the levelized cost of energy method are employed to model the benefits of wind farms and CHP plants, following the approach proposed in [16].

The profit concession from Player W and the subsidies for the installed EB capacity from both Player G and Player W directly impact the EB investment from Player C; which affects their benefits from this project.

Player G obtains a social benefit from additional wind power accommodation while offering subsidies to Player C for the capacity installation of EBs.

Player W provides a profit concession according to his profits from extra wind power accommodation and provides one-off subsidies to Player C based on the installed EB capacity.

Installing EBs decreases Player C's power supply and production costs by decreasing Player C's heat supply. Player C receives a profit concession from Player W, realizes savings from decreasing the production cost with correspondingly less output, makes less income due to the decreased sale of electricity, and pays for the installed EB capacity, with the exception of the subsidy proportion from the remaining two players.

Their utilizations are calculated as

$$U_G = Q \times e - P_B \times c_1 \times S_G \tag{7}$$

$$U_W = Q \times p_1 \times (1 - R_W) - P_B \times c_1 \times S_W \tag{8}$$

$$U_C = Q \times p_1 \times R_W + Q/\theta \times c_2 - Q \times p_2 - P_B \times c_1 \times (1 - S_G - S_W) \tag{9}$$

As game decisions are one-shot decisions, annual values are used to calculate the game results.

2.2.3. Game Analysis for the Unit Cost of CHP Plants

As shown in Formula (9), the accounting method of the unit cost c_2 to supply electricity in a CHP plant affects the profit of Player C and his utilization and action. Less profit is associated with a high unit cost when the electricity price is fixed. Player C tends to declare a low cost to claim higher compensation from his counterparts, whereas Player W prefers to use a high cost accounting method to pay for a smaller calculated loss of Player C. Therefore, determining the accounting method of c_2 is a contradiction in this game.

The marginal cost and average cost are the most common measures for determining the unit production cost. The marginal cost is typically employed when profits are determined, excluding fixed asset investments, whereas the average cost is employed when profits, including fixed asset investments, are calculated [26].

All decisions and actions of the three stakeholders are dependent on the profit variation of Player C. Player C prefers to calculate his profit using marginal costs, which are low cost to receive higher compensatory payment in this project. However, Player W prefers to use the average cost to measure Player C's cost to obtain an advantage when bargaining with Player C for the compensatory payment. Thus, c_2 will be set in the process of the game action between Player W and Player C.

We introduce a payoff function, which is extensively applied in game theory to represent player utilization, to analyze how c_2 is determined. The payoff functions of Player C and Player W for the accounting of unit cost c_2 are assumed to be linear [27], as represented by Line AB and Line OC shown in Figure 3.

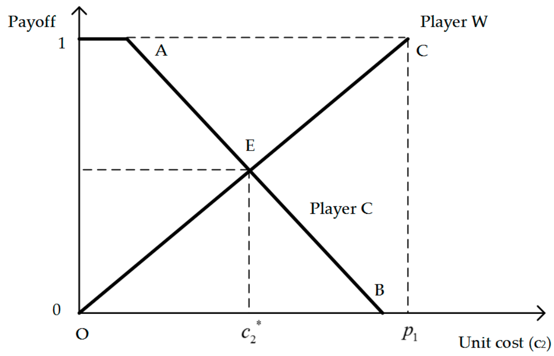

Figure 3. Payoff functions of Player W and Player C.

In Figure 3, Point A and Point B are two extreme situations of Player C's payoff: Player C has the lowest payoff at Point B when the unit cost reaches its maximum value (average cost) and the highest payoff at Point A (marginal cost). Point O and Point C are two extreme situations of Player W's payoff function. As Player W does not know the exact unit cost of Player C, he has to speculate this cost according to information that he has obtained. He believes that the lowest unit cost is zero and that the highest cost is p_1, beyond which Player C would buy wind power to sell rather than generate electricity.

Therefore, Point E, which is the intersection of Line AB and Line OC, is the equilibrium of the game, where the unit cost c_2^* of Player C can be calculated as

$$c_2^* = \frac{c_B \times p_1}{c_B + p_1 - c_A} \tag{10}$$

where c_A and c_B are the marginal unit cost and the average unit cost, respectively, that correspond to Point A and Point B, respectively, in Figure 3.

2.3. Approach and Tricks for Solving the Model

Player C will give an investment response of P_B to maximize his utilization for any given set of $(S_G, S_W,\ R_W)$. Player W can determine his optimum tactic of $(S_W, R_W,)$ by examining all responses of Player C for the scenario of the given S_G. Then, Player G determines his optimum S_G by examining all responses of Player W.

A function of real wind power curtailment is a main requirement for this project; however, it is not usually available due to its irregularity. A Monte Carlo-based simulation is suggested to approximate this function. First, wind speed is obtained by Monte Carlo, following the process proposed in [16], and the theoretical wind power output is estimated using a wind speed–power relationship curve. Next, the wind power curtailment is simulated by calculating the gap between the load demand and the obligatory output of the power system.

Formula (6) is resolved by searching the optimum set of the following four variables: the subsidy ratio from Player G, the subsidy ratio from Player W (S_G, S_W), the profit concession R_w, and the installed EB capacity P_B. Obtaining an optimum solution for Formula (6) is difficult using a mathematic optimization method. Here, an approximate enumeration method is proposed for this solution. We construct a discrete space of these four variables to approximate their solution space, in which S_G, S_W, and R_W are examined from 0% to 100% with a step of 1%, and P_B is examined with a step of 1% in the installed EB capacity.

3. Case Study

3.1. Data Sources and Background

The real data of the BTH power grid are employed in this paper. In 2015, the minimum electric load was approximately 37,000 MW, the installed CHP generator capacity was 25,000 MW, and the wind power curtailment ratio was 7.8%. Details are provided in [16]. As additional CHP plants are reconstructed from condensing units in the incentive policy of the Chinese government, the capacity of the grid to accommodate wind power has decreased, and concerns about grid security have increased. The BTH power grid should ensure sufficient future capacity for operation security while accommodating current wind power. We received funding from the BTH power grid to determine a solution to this issue. In a previous study, we suggested exploiting EBs to increase the flexibility of CHP plants and concluded that the optimum capacity of the BTH grid is 1100 MW. However, who should invest in EBs, how to encourage them to invest, and how to design an investment incentive mechanism have not been discussed. This paper aims to resolve these issues.

3.2. Effect of EBs on Wind Power Accommodation

The average thermoelectric ratio of a typical CHP plant in BTH with a rated power of 300 MW is calculated to be 6.67 GJ/MWh. Some excellent EBs' thermoelectric conversion efficiency is nearly 100%. We assume that EBs with a rated power of 30 MW supply heat at 108 GJ/h and that 1 kWh = 3.6×10^6 J. Therefore, the effectiveness of EBs for wind power accommodation θ is 1.54 according to the calculation from Formulas (1)–(3). This result indicates that an additional 1.54 kWh of wind power will be accommodated for every kWh of electricity that is consumed by the EBs.

The additional parameter values that are employed for the calculations are listed in Table 1.

Table 1. Parameter values.

Parameter	Meaning	Value	Units
e	Environmental emissions cost of the power sector	0.0109	US $/kWh
c_1	Annual value of EB investment cost per unit	7253.63	US $/kWh
p_1	Unit profit of wind power	0.0740	US $/kWh
p_2	Unit price of power supplied by the CHP plant	0.0725	US $/kWh
$c_2{}'$	Average unit cost of CHP units	0.0551	US $/kWh
$c_2{}''$	Marginal unit cost of CHP units	0.0174	US $/kWh

Data resource: e is discussed in [28,29]; c_1 is calculated according to [16]; and the remaining data are assessed using actual data from typical plants and the grid of BTH in 2016. The parameter values are measured in the Chinese currency RMB Yuan and are converted to US dollars in the analysis at the rate of 1 US $ = 6.8931 Yuan, comparing the U.S. dollar against the RMB exchange rate.

3.3. Game Results

Using the approach presented in Section 2.3 to solve the model with the previously mentioned parameters, we computed it in MATLAB and obtained all game outcomes for different government subsidy scenarios. The government can identify the best subsidy option by comparing these outcomes. The game results can be described as follows: the equilibrium results of the game are listed in Table 2 based on the annual value calculation.

Table 2. Main results.

Item	Government	Wind Farms	CHP Plants
Subsidies (US $/MW)	1305.65	5802.90	−7108.56
Profit concession (US $/kWh)	-	0.0599	−0.0205
Investment (MW)	-	-	1110
Benefits (US $)	4.95×10^6	1.93×10^6	4.58×10^4
Return on investment (%)	341.34	29.93	28.50

Among the total 7253.63 US $/MW annual investment, all EB capacity investment from the CHP plant is only 145.07 US $/MW with the 7108.56 US $/MW of subsidies from government and wind farms.

The subsidies provided by the government to the CHP plants for the installed EB capacity is 1305.65 US $/MW, where the social benefit reaches its peak value, as shown in Figure 4.

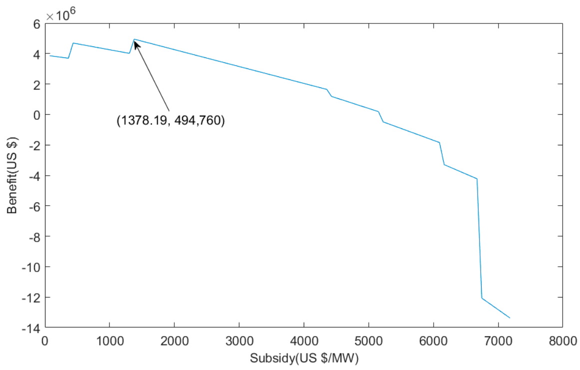

Figure 4. Benefits of government.

The subsidy from wind farms to CHP plants for the installed EB capacity is 5802.90 US $/MW, and the profit concession based on the quantity of accommodated wind power is 0.0599 US $/kWh for the scenario with government subsidies of 1305.65 US $/MW, as shown in Figure 5.

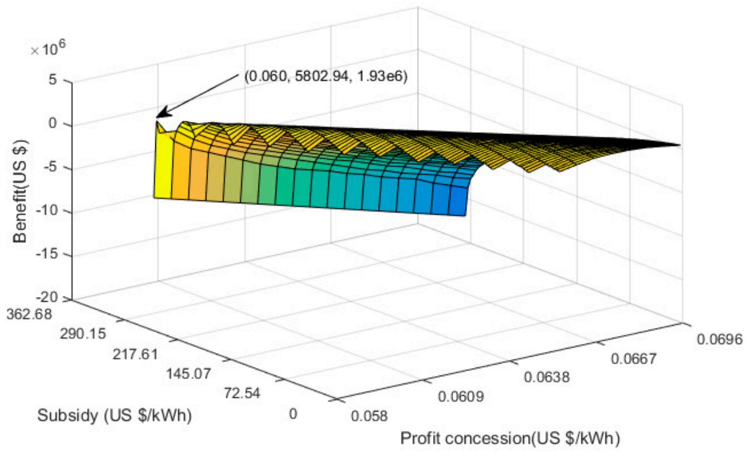

Figure 5. Benefits of wind farms.

Figure 6 shows the benefits of CHP plants with government subsidies of 1305.65 US $/MW, wind farm subsidies of 5802.90 US $/MW, and wind farm profit concessions of 0.0599 US $/kWh. This figure indicates that the optimum installed EB capacity for the CHP plants is 1110 MW, which is similar to the capacity of 1100 MW suggested in [16], which validates the proposed model.

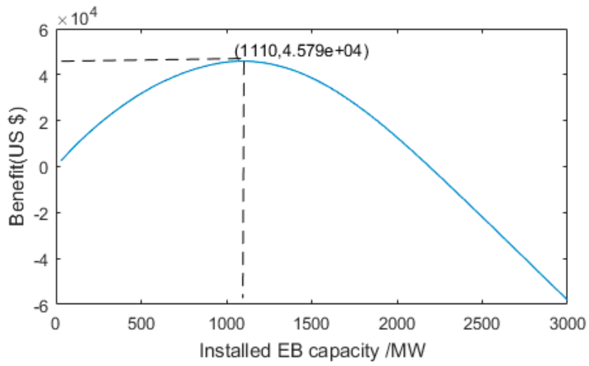

Figure 6. Benefits of CHP plants with varying installed EB capacity.

Installing 1110 MW of EBs will reduce the CHP output by 10% in the valley load period, which will increase the peak regulation margin by 1400 MW. The optimum installed EB capacity will be implemented by CHP plants with the minimum government subsidy.

4. Conclusions

This paper investigated the government subsidy mechanism for promoting EBs to accommodate wind power. This study developed a game model to simulate the decision process of the involved parties and calculated the minimum government subsidy that would maximize social benefits while maximizing the benefits of both wind farms and CHP plants. An approximate enumeration technique to analyze the effect of the EB investment on both wind farms and CHP plants was employed to determine their optimum actions. A case study was conducted using the data of the BTH grid in 2015.

The results of the game model indicated that if the government provides an annual subsidy of 1305.65 US $/MW to the CHP plants for the EB investment, then the optimum installed EB capacity of 1110 MW will be achieved.

Some improvements could be achieved in future studies. This paper attempted to make a decision from the government perspective, assuming that CHP plants will accept any profitable proposal. However, the CHP plant may desire profits beyond those proposed in this model as they have considerable influence on this investment decision. Furthermore, wind farms can participate in this project and act individually rather than being regarded as a single player; the same notion is valid for CHP plants. Therefore, the actual game analysis will be substantially more complex.

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Author Contributions: Da Liu and Shoukai Wang conceived and designed the experiments; Shoukai Wang and Jinchen Liu performed the experiments; Da Liu and Yi Feng analyzed the data; Shoukai Wang and Han Huang wrote the paper; Da Liu and Jinchen Liu finalized the manuscript in discussion with Xingping Zhang and Weijun Wang.

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

Nomenclature

BTH	Beijing–Tianjin–Hebei
CHP	Combined heat and power
EBs	Electric boilers
Player C	CHP plants
Player G	Government
Player W	Wind farms

Symbols

c_1	Unit cost of the EB investment
c_2	Unit cost of Player C's electricity power production
$c_2{\prime}$	Unit cost of CHP units
$c_2{''}$	Marginal unit cost of CHP units
c_2^*	Unit cost
c_A	Marginal unit cost
c_B	Average unit cost
e	Unit environmental emissions cost of the power sector
E	Electric power generated by CHP units before employing EBs
H	Heat generated by CHP units before employing EBs
kW	Kilowatt
MW	Megawatt
p_1	Unit profit of Player W gained from this project
p_2	Unit cost of supplying electricity for Player C
P_B	Capacity of EBs to be invested
P_{w_t}	Wind power curtailment at time of t
Q	Quantity of wind power accommodation after employing EBs
R_W	Profit concession from Player W to Player C
S_G	Subsidy from Player G to Player C
S_W	Subsidy from Player W to Player C
t	Time of t
U_C	Utilization of Player C
U_G	Utilization of Player G
U_W	Utilization of Player W
v	Dummy variable that indicates whether this project can complete prevent wind power curtailment
Δt	Duration of each time segment

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