Research on the Income Mechanism and Investment Strategy of Additional Heat Source in Combined Heat and Power System

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Abstract. Utilization of additional heat sources (AHS), such as electric boilers and heat storage tanks, is an effective way to promote the wind power consumption in large scale combined heat and power system (CHPS) in northern China. To promote the construction and operation of the AHS, this paper proposed a market mechanism that thermal power plant and wind farm share the benefits and investment risks of AHS together. A novel market mechanism of AHS including income mechanism and investment strategy is proposed. Under this market mechanism, the following aspects are studied: (1) The cost and income model of each subject is derived; (2) The feasible region of invest and income proportion of each participant is analysed; (3) The optimal investment strategy of multi participants is built. At last, actual example simulations is conducted to demonstrate the effectiveness of the proposed market mechanism. Simulation results show that the proposed method can arouse the enthusiasm of wind farm and thermal power plant and promote the construction and operation of the AHS, which has a certain significance to promote wind power consumption in combined heat and power system.

1. Introduction

Recently, combined heat and power system (CHPS) and wind power curtailment are hot topics in research field, and they are also an important part of the integrated energy system [1,2]. Due to the anti-peak regulation characteristics of wind power and thermal-electric coupling constraint of CHP units, high heat load demand increases the lower limit of electrical output of CHP units, which causes the high incidence of wind power curtailment. To solve this problem, many experts have made relevant research to enhance the capacity of wind power consumption in CHPS.

There are mainly three methods: (1) Using the heat storage characteristics and thermal inertia of the district heating system to optimize of heat load profiles [3]. (2) “Wind power heating” [4]. (3) Allocate AHS to reduce thermal-electric coupling [5,6].

In this paper, a novel market mechanism of AHS including income mechanism and investment strategy is proposed. Under this market mechanism, the following aspects are studied: (1) The income
model of each subject is established; (2) The feasible region of investment and income proportion of each AHS is analyzed; (3) The optimal investment strategy of multi participates is built. Finally, we have verified the effect of this mechanism by a practical example. The results show that the proposed income mechanism and investment strategy can maintain the interests of all the thermal power plants and wind farms, which has a certain significance for the construction and operation of AHS in CHPS.

2. Profit market mechanism model

2.1. Brief description of the income mechanism and investment strategy

In this paper, the core idea of the proposed market mechanism is that thermal power plant and wind farm share the income and investment risks of AHS jointly. A brief diagram of proposed market mechanism is shown in Fig. 1

![Figure 1. Brief diagram of proposed market mechanism model.](image)

To promote the wind power consumption, a thermal power plant may be equipped with multiple AHS. And for a specific AHS \( i \), there are two investors, one is the wind farm, the other is a thermal power plant \( k \). The investment proportion of thermal power plant is \( \beta_i \), and the investment proportion of wind farm is \( 1-\beta_i \). After that, AHS \( i \) may increase the wind power consumption so that the income is also increased. Then, thermal power plant and wind farm share the income. The income proportion of thermal power plant is \( \alpha_i \), and income proportion of wind farm is \( 1-\alpha_i \).

2.2. Analysis of the income model of each participant

2.2.1. Modeling of thermal power plants’ income. For a specific heat sources, we assume that the heat source \( i \) is built in the thermal power plant \( k \) and its initial investment cost is \( \sum_0 I_{AHS,i} \). The cost of the thermal power plant’s investment in AHS \( i \) can be expressed as:

\[
\Delta_{\text{CHP},j}^k = \beta_i \cdot I_{20,\text{AHS},j}
\]  

Where, \( \Delta_{\text{CHP},j}^k \) is the initial investment cost of thermal power plant \( k \) in AHS \( i \), \( I_{20,\text{AHS},j} \) is the initial investment of AHS \( i \). For electric boilers, \( I_{20,\text{AHS},j} = C_{EB,j} \cdot I_{20,EB} \); for heat storages, \( I_{20,\text{AHS},j} = C_{HS,j} \cdot I_{20,HS} \).

After AHS is allocated, there will be some changes in the operating status of the thermal power plant. For example, thermal power plants will increase the supply of heat sources, and thermal power plants will reduce the amount of electricity sold on the grid. As the heat source heating and thermal power plants reduce a part of the heat supply. After the AHS heating, the thermal power plant will reduces part of the heat supply. These conditions will have a certain degree of impact on the income of thermal power plants. Therefore, it is necessary to quantify the participants’ income changes after heat sources consume “abandon wind”. Firstly, based on the incremental equation of electric load and heat load balance, the power generation and heating output changes of thermal power plant are obtained, to
obtain the cost and profit variation model of the thermal power plant. And then the income variation of thermal power plant can be analyzed. Thermal power plant revenue changes are mainly divided into the following sections: power supply cost of AHS, the opportunity cost of decreased electricity sales in a thermal power plant, the cost of reducing heat supply of a thermal power plant, maintenance cost of AHS and the compensation income obtained of thermal power plant.

(a) Power supply costs of AHS.

After the heat source is deployed in a thermal power plant, its operation requires the power supply of the thermal power plant, which will result in a loss of income for thermal power plants. For the electric boiler, electric balance incremental equation is shown in (2), heat balance incremental equation is shown in (3).

\[ \Delta W_{\text{CHP,EB},i} + \frac{1}{\gamma_{\text{CHP},j}} \Delta Q_{\text{CHP,EB},i} = \Delta W_{\text{wind},i} \] (2)

\[ \Delta Q_{\text{CHP,EB},i} = \beta_{\text{EB}} \Delta W_{\text{CHP,EB},i} \] (3)

Where, \( \Delta W_{\text{CHP,EB},i} \) is the power consumption of electric boiler \( i \) operation, \( \Delta Q_{\text{CHP,EB},i} \) is the heat output of electric boiler \( i \). According to (2) and (3), when the wind consumed by electric boiler is \( \Delta W_{\text{wind},i} \), the power consumption of the electric boiler is:

\[ \Delta W_{\text{CHP,EB},i} = \frac{\gamma_{\text{CHP},j}}{\beta_{\text{EB}} + \gamma_{\text{CHP},j}} \Delta W_{\text{wind},i} \] (4)

The electric balance incremental equation and heat balance incremental equation of heat storage is shown in (5) and (6) respectively.

\[ \Delta W_{\text{CHP,HS},i} + \frac{1}{\gamma_{\text{CHP},j}} \Delta Q_{\text{out,HS},i} = \Delta W_{\text{wind},i} \] (5)

\[ \Delta W_{\text{CHP,HS},i} = \rho_{\text{HS}} \Delta Q_{\text{out,HS},i} \] (6)

Where, \( \Delta W_{\text{CHP,HS},i} \) is the power consumption of heat storage \( i \) and \( \Delta Q_{\text{out,HS},i} \) is the heat output of heat storage during the wind power curtailment period. According to (4) and (6), the power consumption of heat storage can be expressed as:

\[ \Delta W_{\text{CHP,HS},i} = \frac{\rho_{\text{HS}} \gamma_{\text{CHP},j}}{1 + \rho_{\text{HS}} \gamma_{\text{CHP},j}} \Delta W_{\text{wind},i} \] (7)

If the AHS \( i \) is allocated in thermal power plant \( k \), the increased power supply in thermal power plant \( k \) can be simplified as:

\[ \Delta W_{\text{CHP,EB},i} = \lambda_{i} \Delta W_{\text{wind},i} \] (8)

Where, \( \Delta W_{\text{CHP,EB},i} \) is the increased power supply of AHS \( i \) in thermal power plant \( k \). \( \lambda_{i} \) is a conversion coefficient. According to (4) and (6), for different kinds of AHS, \( \lambda_{i} \) is different, as shown in (9).
\[ \lambda_i = \begin{cases} \frac{\gamma_{\text{CHP},i}}{\beta_{\text{EB}} + \gamma_{\text{CHP},i}}, & \text{AHS=EB} \\ \frac{\rho_{\text{HS}}\gamma_{\text{CHP},i}}{1 + \rho_{\text{HS}}\gamma_{\text{CHP},i}}, & \text{AHS=HS} \end{cases} \] (9)

According to the increased power supply of the thermal power plant, the additional power supply cost can be obtained as follows:

\[ \Delta R_{\text{CHP},i,j}^k = \Delta W_{\text{wind},j} \] (10)

Where, \( \Delta R_{\text{CHP},i,j}^k \) is the increased power supply cost of thermal power plant \( k \) to AHS \( i \), \( c_{\text{coal},e,k} \) is the power generation cost of thermal power plant \( k \), \( \rho_{\text{coal},e,k} = \mu_{\text{coal},e,k} \cdot v_{\text{coal}} \cdot v_{\text{coal},e,k} \) is the power generation coal consumption rate of thermal power plant \( k \) and \( v_{\text{coal}} \) is the coal price.

(b) The opportunity cost of decreased electricity sales in a thermal power plant.

Because the total electrical load of the system is constant, the reduction of electricity consumption of the thermal power plant is equal to that of the wind power consumed by the heat source. Therefore, after the heat source is operation, the reduction in electricity sales and the reduction in electricity sale income of thermal power plants are shown in (11) and (12) respectively.

\[ \Delta W_{\text{CHP},i,j}^k = \Delta W_{\text{wind},j} \] (11)

\[ \Delta R_{\text{CHP},i,j}^k = (v_{\text{elec}} - c_{\text{coal},e,k}) \cdot \Delta W_{\text{wind},j} \] (12)

Where, \( \Delta W_{\text{CHP},i,j}^k \) is the reduction in electricity sales of thermal power plant \( k \), \( \Delta R_{\text{CHP},i,j}^k \) is the reduction in Electricity sale income of thermal power plant \( k \), \( v_{\text{elec}} \) is the electricity sale price of thermal power plant.

(c) The cost of reducing heat supply of a thermal power plant.

During the wind power curtailment period, AHS will supply part of heat load instead of thermal power plants, which will reduce the heating costs of thermal power plants. For electric boilers, according to their electric-thermal balance increment equations (2) and (3), the reduction in heat supply of thermal power plant can be expressed as:

\[ \Delta Q_{\text{CHP,EB},j} = \frac{\beta_{\text{EB}}\gamma_{\text{CHP},i}}{\beta_{\text{EB}} + \gamma_{\text{CHP},i}} \Delta W_{\text{wind},j} \] (13)

Where \( \Delta Q_{\text{CHP,EB},j} \) is the reduction in heat supply of thermal power plant due to the operation of electric boiler. And for heat storage, it stores heat during daytime and releases heat during the period of wind abandonment at night, realizing the heat load optimization. The heat supply in a thermal power plant is unchanged for a whole period. Therefore, after heat storage operation, the cost of reducing heat supply of a thermal power plant equals to 0.

In summary, the cost of reducing heat supply of a thermal power plant after AHS configuration.

\[ \Delta Q_{\text{CHP},i,j,3}^k = \delta_i \Delta W_{\text{wind},j} \] (14)

Where, \( \delta_i \) is a coefficient which is shown as following:
EB CHP, EB CHP, EB
AHS = 0, AHS = i

\[ \beta \gamma \delta = \begin{cases} \beta_{EB}^{CHP,i}, & \text{AHS=EB} \\ \beta_{EB} + \gamma_{CHP,i}, & \text{AHS=HS} \\ 0, & \end{cases} \]  

(15)

So the coal saving benefits brought by AHS \( i \) in thermal power plants \( k \) is:

\[ \Delta R_{CHP,i,3}^{k} = \beta_{i} \cdot c_{coal,h,k} \cdot \Delta W_{wind,i} \]  

(16)

Where, \( \Delta R_{CHP,i,3}^{k} \) is the reduction in the heating cost of the thermal power plant \( k \), after the AHS \( i \) configuration, \( c_{coal,h} \) is the heat generation cost of thermal power plant \( k \), \( c_{coal,h,k} = \mu_{coal,h,k} \cdot v_{coal} \cdot \mu_{coal,h,k} \) is the heat generation coal consumption rate of thermal power plant \( k \) and \( v_{coal} \) is the coal price.

(d) The compensation income obtained of thermal power plant.

After the heat source consumes wind power, the wind farm should compensate a part of the income to the thermal power plant. This can mobilize the enthusiasm of thermal power plants to participate in the construction and operation of heat sources and promote the coordinated operation of AHS and CHP units.

\[ \Delta R_{CHP,i,5}^{k} = \alpha_{i} \cdot c_{wind} \cdot \Delta W_{wind,i} \]  

(17)

Where, \( \Delta R_{CHP,i,5}^{k} \) is the compensation income of thermal power plant \( k \) from AHS \( i \), \( v_{wind} \) is the electricity sale price of wind farm. To sum up, from the perspective of short-term real-time operation, when AHS consumed unit wind power, the short-term income of thermal power plants is:

\( \Delta R_{CHP,i}^{k} = \left( -\Delta R_{CHP,i,1}^{k} - \Delta R_{CHP,i,2}^{k} + \Delta R_{CHP,i,3}^{k} + \Delta R_{CHP,i,5}^{k} \right) / \Delta W_{wind,i} \)  

(18)

Where, \( \Delta R_{CHP,i}^{k} \) is the income of thermal power plants from unit wind power consumption, (17) can be organized and simplified as:

\[ \Delta R_{CHP,i}^{k} = \alpha_{i} v_{wind} + \beta_{i} c_{coal,h} + (1 - \lambda_{i}) c_{coal,e} - v_{elec} \]  

(19)

From the mid-term and long-term perspective, according to the annual wind power consumption of AHS \( i \), the increased annual income of thermal power plant \( k \) is:

\[ \Delta R_{CHP,i}^{k} = \Delta W_{wind,year}^{k} \cdot \left[ \alpha_{i} v_{wind} + \beta_{i} c_{coal,h} + (1 - \lambda_{i}) c_{coal,e} - v_{elec} - v_{AHS,i} \right] \]  

(20)

Where, \( \Delta W_{wind,year}^{k} \) is the annual wind power consumption of AHS \( i \), \( \Delta R_{CHP,i}^{k} \) is the annual income of thermal power plant \( k \) from AHS \( i \). Assuming that the annual net cash flow does not change, the total profit of thermal power plant \( k \) from AHS \( i \) during the whole service life can be expressed as:

\[ \Delta E_{CHP,i}^{k} = Y_{L} \cdot \Delta R_{CHP,i}^{k} = Y_{L} \cdot \Delta W_{wind,year}^{k} \cdot \left[ \alpha_{i} v_{wind} + \beta_{i} c_{coal,h} + (1 - \lambda_{i}) c_{coal,e} - v_{elec} - v_{AHS,i} \right] \]  

(21)

Where, \( \Delta E_{CHP,i}^{k} \) is the total profit of thermal power plant \( k \) from AHS \( i \) during the whole service life, \( Y_{L} \) is the service life of AHS. Each thermal power plant can be allocated with multiple different types of AHS. Therefore, the comprehensive static investment return period of thermal power plant \( k \) for all AHS can be expressed as following:
Where comprehensive static investment return period of thermal power plant \(k\), \(N_{AHS,k}\) is the total number of AHS in thermal power plant \(k\).

### 2.2.2. Modeling of wind farms’ income.

The investment by wind farm in AHS \(i\) can be expressed as:

\[
\Delta I_{WF,i} = (1 - \beta_i) \cdot I_{\Sigma 0,AHS,i}
\]

(23)

Where, \(\Delta I_{CHP,i}\) is the initial investment cost of wind farms in AHS \(i\), \(1-\beta_i\) is the investment proportion of wind farm Compared to thermal power plants, the income model of wind farms is simpler. From the perspective of short-term real-time operation, when AHS consumed unit wind power, the short-term income wind farms is shown in the following equation:

\[
\Delta R_{WF,i} = (1 - \alpha_i) \cdot \gamma_{wind}
\]

(24)

Where, \(\Delta R_{WF,i}\) is the income of wind farms from unit wind power consumption. From the mid-term and long-term perspective, according to the annual wind power consumption of AHS \(i\), the increased annual income of wind farms from AHS \(i\) is:

\[
\Delta R_{WF,i} = (1 - \alpha_i) \cdot \Delta W_{wind,i}^\text{year} \cdot \gamma_{wind}
\]

(25)

Where, \(\Delta R_{WF,i}\) is the annual income of wind farms from AHS \(i\). According to the annual income shown in (25), the total profit of wind farms from AHS \(i\) during the whole service life is:

\[
\Delta E_{CHP,i} = Y_L \cdot \Delta R_{WF,i}^k - \Delta I_{WF,i}^k = Y_L \cdot \Delta W_{wind,i}^{\text{year}} \cdot (1 - \alpha_i) \cdot \gamma_{wind} + \Delta \delta c_{coal.h}^{\text{Year}} + (1 - \lambda_i) c_{coal.e} - v_{\text{elec}} - \theta_{AHS,i} - (\varepsilon_{AHS,i} + \beta_i) I_{\Sigma 0,AHS,i}
\]

(26)

And the comprehensive static investment return period of wind farms for all AHS can be expressed as following:

\[
Y_{WF} = \frac{\sum_{i=1}^{N_{AHS}} \Delta I_{WF,i}^k \cdot (1 - \beta_i) \cdot I_{\Sigma 0,AHS,i}}{\sum_{i=1}^{N_{AHS}} \Delta R_{WF,i}^k \cdot (1 - \alpha_i) \cdot \Delta W_{wind,i}^{\text{year}} \cdot \gamma_{wind}}
\]

(27)

Where, \(Y_{WF}\) is the comprehensive static investment return period of wind farms.

### 3. Case Study

#### 3.1. Parameters of simulation model

Simulation system derive from a city of Jilin province, northeast of China. The structure of the system is shown in Fig. 2
To promote the wind power consumption of this regional power system, some AHS (electric boiler and heat storage) have been configured in each district heating areas. The configuration information of AHS is shown in Table 1.

Table 1. Basic document specifications.

| District heating area | Electric Boiler (MW) | Heat Storage (MWh) |
|----------------------|----------------------|-------------------|
| 1                    | 45                   | 920               |
| 2                    | 30                   | 540               |
| 3                    | 25                   | 200               |

According to the historical statistics of this regional CHPS, the wind power consumption amount of each AHS can be obtained by production simulation, as shown in Fig 3. If the wind farm does not make compensation for the thermal power plant, the income of different participants varies with the wind power consumption are shown in Fig. 4.

From Fig. 4, it can be concluded that if there is no compensation income, conventional thermal power plans will face losses and wind farms will gain much profits. This will reduce the enthusiasm of thermal power plants to participate in the construction and operation of AHS. Therefore, after the AHS consumed wind power, it is necessary for the wind farm to compensate part of profits to the thermal power plants.
3.2. Analysis of feasible region

In this paper, we assumed that the probability density of wind power consumed by AHS obey normal distribution. Besides, the simulation value of wind power consumption amount is taken as the normal distribution mean value and the standard deviation values of normal distribution is set equal to 1.

Different participants may hold different risk attitude of wind power consumed by an AHS. To describe the risk attitude of each participant, this paper introduce the parameter of confidence level $c_i$, which represent risk attitudes and estimation of wind power consumption.

For a particular participant, such as a wind farm or a thermal power plant, according to its confidence level $c_i$, the estimation of all the participant on wind power consumption $\Delta W_{\text{wind},j}^{\text{EST}}$ can be determined.

$$
    c_i|_{\Delta W_{\text{wind},j}^{\text{EST}} > \Delta W_{\text{wind},j}^{\text{EST}}} = \int_{\Delta W_{\text{wind},j}^{\text{EST}}}^{\infty} f(\Delta W_{\text{wind},j}) d\Delta W_{\text{wind},j}
$$

(28)

Where $c_i$ is the confidence level of the investor to the AHS $i$, $\Delta W_{\text{wind},j}^{\text{EST}}$ is the estimation value of wind power consumed by AHS $i$.

As the confidence level $c$ changes from 0.3 to 0.9, and coal price changes from 60 $/t to 180 $/t, the variations of invest and income feasible region are shown in Fig. 5 and Fig. 6 respectively. The red line in the figure is the acceptable marginal curve of different CHP plants and the blue line is the acceptable marginal curve of wind farm. The region between this two lines is the feasible region that both side is acceptable.

![Image](https://via.placeholder.com/150)

**Figure.** 5. Invest and income feasible region changes with confidence level.
From Fig. 5 to Fig. 6, we can get the following conclusion:

1) With the increasing of confidence level, the feasible region is becoming smaller. The reason is that the confidence level represent the risk attitude of the participant. The larger the confidence level is, the smaller the estimation wind power consumption is, which results in less prediction income of the project.

2) The coal price can also influence the feasible region of invest and income proportion. The difference is that the coal price can only influence the marginal curve of different CHP plants (the lower limit) and have no effect on marginal curve of wind farm. With the increasing of coal price, CHP plants will be more willing to participate in the operation of AHS. It is worth mentioning that when the coal price is high enough, the power generation in a CHP plant will bring great losses, so the CHP plants are willing to reduce power generation output and participate the operation of AHS.

The optimal result of payback period of different participant is shown in Fig. 7. It shows the static payback period of all the participant including CHP plants and wind farm. Simulation results show that the proposed income mechanism and investment strategy can ensure that the payback period of each participant is as close as possible and effectively satisfy the interests of all participants, which helps to maintain fairness among the various entities. When the compensation proportion is large enough, the optimization result is close to the boundary of feasible region and the payback period of different participants are becoming different.

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**Figure 6.** Invest and income feasible region changes with coal price $v_{\text{coal}}$.

**Figure 7.** Payback period of each participant changes with compensation proportion.
4. Conclusion
In this paper, a novel market mechanism including Income Mechanism and Investment Strategy of Additional Heat Source in Combined Heat and Power System has been proposed. Under this market mechanism, the following aspects have been studied: (1) The incremental income model for each AHS participant is established; (2) The feasible region of investment and income proportion of each AHS has been analyzed; (3) The optimal investment strategy of multi participates is built. Finally, the effect of this mechanism is verified by a practical example and various factors that influence the feasible region are analysis. Simulation results show that the proposed income mechanism and investment strategy can ensure that the payback period of each participant is as close as possible and effectively satisfy the interests of all participants, which has a certain significance for the construction and operation of AHS in CHPS.

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