The Profit Influence of Additional Heat Sources on Combined Heat and Power System in Existing Peak Shaving Compensation Mechanism

Yang Bai[1], Jianxing Qin[2], Qi Guo[3] and Zhongkai Yi[3]

[1] Guangdong Power Grid Dispatching Control Center, Guangzhou 510600, China
[2] Guangzhou Yiyun Information Technology Co., Ltd, Guangzhou 510275, China
[3] School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, China
E-mail: Gqtiffany@163.com

Abstract. In combined heat and power system, configuring of electric boilers, heat storage and other additional heat sources (AHS) is an effective way to alleviate the problem of wind curtailment in northeast China. In this paper, according to the currently existing peak shaving compensation mechanism, a production simulation model with AHS has been established. Based on them, the impact of AHS on the profit of combined heat and power (CHP) units, conventional (CON) units and wind farms is analyzed. Simulation system derives from a city of Jilin province, northeast of China, simulation result shows that with AHS involved, wind farms benefit most, and CHP units face profit decline. Besides, this paper also gives some advice to promote the configuration and operation of AHS, which has a guiding significance for the improvement of peak shaving compensation mechanism.

1. Introduction

In northeast China, CHP units are the main heating sources in winter, and their proportion is considerable. The use of CHP units, electric boilers and heat pumps creates linkages between electricity and heat networks [1]. Because of the opposite peak-valley characteristics of power load and heat load and the constraint of thermal-electrical coupling of CHP units, the CHP units have to output more power in heating consuming peak time. Therefore other thermal power plants have to regulate depth peak load cycling, even shut down directly, which increase the difficulties of peak shaving.

Recent years, large-scale grid integration of wind power further exacerbates the difficulty of peak shaving. As a result, wind curtailment often occurs in northeast China and the maximum wind-removal rate is even above 20% [2]. Especially in northeast China, the areas which are rich of wind resource also badly need heating in winter, and the higher proportion of thermal power units adversely affects the wind power consumption.

There are mainly three methods to solve the problem of wind power curtailment: (1) Using the characteristics of district heating system such as heat storage characteristics and thermal inertia to consume the wind power [3]. (2) 'Wind power heating' [4]. (3) Allocating additional heat source (AHS) to reduce thermal-electric coupling [5]. Among them, the third way of allocating AHS is effective to promote wind power consumption. AHS include the electric boiler, heat storage and heat pumps and so on [6], [7]. In the literature [6], the optimal allocation method of AHS is studied. In the literature [7], the heat storage is used to reduce the thermal-electric coupling of CHP units. Ref [8]-[10]

show that the electric boiler can promote the wind power consumption and the heat storage can increase the economic efficiency of the whole system.

In this paper, a production simulation model of heating season with AHS is established. The power generation of CHP units, CON units and wind farms are obtained, both with and without AHS. And according to the existing power peak shaving compensation mechanism, the profit of each unit participated in the power market can be calculated. Based on them, this paper aims to analyze the profit influence of AHS on combined heat and power system and wind farms, then puts forward reasonable suggestions for the improvement of the power peak shaving compensation mechanism.

2. Mechanism of AHS to relieve wind curtailment

The policy of planning and operating CHP units based on 'Ordering Electricity by Heat' limits the lower heat output limit of CHP units during the heating season, which exacerbates the phenomenon of wind power curtailment. The AHS can improve the peak shaving capacity of CHP units. Arranging the heat storage and electric boiler inside the thermal power plant can provide extra heat source for the heat network and reduce the heat output demand of CHP units. And it is a good way to release the limited potential for regulation of CHP units, therefore the wind power curtailment during heating season could be relieved effectively.

3. Production simulation model with AHS

3.1. Objective function

In order to increase the utilization rate of new energy sources and relieve wind power curtailment, the cost of wind power generation is excluded in the scheduling model, and the objective function is to minimize the total system coal consumption:

$$\min F = \sum_{t=1}^{T} (\sum_{r=1}^{R} \sum_{n=1}^{N} F_{\text{CHP}}^{t,r,n}(P_{\text{e}}^{t,r,n}, P_{\text{h}}^{t,r,n}) + \sum_{s=1}^{S} F_{\text{CON}}^{t,s}(P_{\text{e}}^{t,s})) \tag{1}$$

Where, F is the minimum system coal consumption; $F_{\text{CHP}}^{t,r,n}$ is the coal consumption of the nth CHP unit at the rth thermal power plant in period t; $P_{\text{e}}^{t,r,n}$ and $P_{\text{h}}^{t,r,n}$ are respectively electric power and thermal power; $F_{\text{CON}}^{t,s}$ is the coal consumption of the sth CON unit in period t; T is the scheduling cycle.

3.2. Unit coal consumption characteristics

The coal consumption characteristics of CON unit is as:

$$F_{\text{CON}} = b_1 + b_2 P_{\text{h}} + b_3 P_{\text{h}}^2 \tag{2}$$

Where, F_{CON} is the coal consumption; P_{h} is the electric power; b_1-b_3 are the fitting coefficients.

The coal consumption characteristics of CHP unit is as:

$$F_{\text{CHP}} = a_1 + a_2 P_{\text{e}} + a_3 P_{\text{e}}^2 + a_4 P_{\text{h}}^2 + a_5 P_{\text{e}} P_{\text{h}} + a_6 P_{\text{h}} \tag{3}$$

Where, F_{CHP} is the coal consumption; P_{e} and P_{h}, respectively, are the electrical power and thermal power; a_1-a_6 are the fitting coefficients.

3.3. Constrains

Electric power balance. Electric power balance formula of CHP unit, CON unit and wind farm in the power grid is:

$$\sum_{r=1}^{R} \sum_{n=1}^{N} P_{\text{CHP}}^{t,r,n} + \sum_{s=1}^{S} P_{\text{CON}}^{t,s} + P_{\text{wind}}^{t} = P_{\text{load}}^{t} + \sum_{r=1}^{R} \sum_{l=1}^{L} P_{\text{e}}^{t,r,l} + \sum_{i=1}^{I} P_{\text{eb}}^{t,i} \tag{4}$$

Where, $P_{\text{CHP}}^{t,r,n}$ is the electric power of the nth CHP unit at the rth thermal power plant in period t ; $P_{\text{CON}}^{t,s}$ is the electric power of the sth CON unit in period t ; P_{wind}^{t} is the total power of the wind farm in period t ; P_{load}^{t} is the electric load in period t ; $P_{\text{eb}}^{t,i}$ is the electric power of the ith electric boiler in period t ; $P_{\text{e}}^{t,r,l}$ is the electric power consumed by the lth heat exchanger station in the rth thermal power plant in period t .

Thermal power balance. In each district heating area, heat load should also be balanced as following:

$$\sum_{n=1}^{N} Q_{\text{CHP}}^{t,r,n} + \sum_{n=1}^{N} Q_{\text{eb}}^{t,r,n} = Q_{\text{load}}^{t}, \quad r = 1,2,...N$$

$$Q_{\text{CHP}}^{t,r,n} = \frac{P_{\text{h}}^{t,r,n} \Delta H^{t,r,n}}{1000} \tag{5}$$

Where, $Q_{\text{CHP}}^{t,r,n}$ is the heat supply of the nth CHP unit at the rth thermal power plant in period t ; $Q_{\text{eb}}^{t,r,n}$ is the heat power of the nth electric boiler at the rth thermal power plant in period t ; Q_{load}^{t} is the heat load in period t ; $P_{\text{h}}^{t,r,n}$ is the extraction of the nth heating unit at the rth thermal power plant in period t ; $\Delta H^{t,r,n}$ is the steam enthalpy drop of the nth heating unit at the rth thermal power plant in period t .

3.4. *Wind power balance.*

$$P_{\text{wind}}^{t,m} + P_{\text{abandon}}^{t,m} = P_{\text{forecast}}^{t,m} \tag{6}$$

Where, $P_{\text{wind}}^{t,m}$ is the amount of wind power actually consumed by the mth wind farm in period t ; $P_{\text{abandon}}^{t,m}$ is the amount of abandonment of the mth wind farm in period t ; $P_{\text{forecast}}^{t,m}$ is the forecast power generated by the mth wind farm in period t .

3.5. *Unit output constrains.*

$$H_{\text{CHP}}^{\min,r,n} \leq H_{\text{CHP}}^{t,r,n} \leq H_{\text{CHP}}^{\max,r,n}$$

$$P_{\text{CHP}}^{\min,r,n} \leq P_{\text{CHP}}^{t,r,n} \leq P_{\text{CHP}}^{\max,r,n}$$

$$P_{\text{CON}}^{\min,r,n} \leq P_{\text{CON}}^{t,r,n} \leq P_{\text{CON}}^{\max,r,n}$$

$$0 \leq P_{\text{wind}} \leq P_{\text{forecast}} \tag{7}$$

Where, $H_{\text{CHP}}^{\min,r,n}$ and $H_{\text{CHP}}^{\max,r,n}$ are respectively the lower limit and the upper limit of the steam extraction amount of the nth CHP unit at the rth thermal power plant in period t ; $P_{\text{CHP}}^{\min,r,n}$ and $P_{\text{CHP}}^{\max,r,n}$ are respectively the lower limit and the upper limit of the electric power of the nth CHP unit at the rth thermal power plant in period t ; $P_{\text{CON}}^{\min,r,n}$ and $P_{\text{CON}}^{\max,r,n}$ are respectively the lower limit and the upper limit of the electric power of the rth CON unit in period t ; P_{forecast} is the forecast power of wind farm.

3.6. *Ramping constrains.*

$$-r_{\text{CHP}}^{\text{down}}\Delta t \le P_{\text{CHP}}^t - P_{\text{CHP}}^{t-1} \le r_{\text{CHP}}^{\text{up}}\Delta t$$

$$-r_{\text{CON}}^{\text{down}}\Delta t \le P_{\text{CON}}^t - P_{\text{CON}}^{t-1} \le r_{\text{CON}}^{\text{up}}\Delta t \tag{8}$$

Where, $r_{\text{CHP}}^{\text{down}}$ and $r_{\text{CHP}}^{\text{up}}$ are respectively the ramping down and ramping up constraints of the CHP unit; $r_{\text{CON}}^{\text{down}}$ and $r_{\text{CON}}^{\text{up}}$ are respectively the ramping down and ramping up constraints of the CON unit.

3.7. *Electric boiler constrains.*

$$P_{\text{eb}}^{\text{min}} \le P_{\text{eb}} \le P_{\text{eb}}^{\text{max}}$$

$$Q_{\text{eb}} = \beta_{\text{eb}}P_{\text{eb}} \tag{9}$$

Where, $P_{\text{eb}}^{\text{min}}$ and $P_{\text{eb}}^{\text{max}}$ are respectively the lower and upper electric power limits of electric boiler. Q_{eb} is the heat output of electric boiler. β_{eb} is the conversion efficiency of electric boiler.

3.8. *Heat storage tank constrains.*

$$0 \le Q_{\text{tank}}^t \le Q_{\text{tank}}^{\text{max}}$$

$$H_{\text{tank}}^t = Q_{\text{tank}}^t - Q_{\text{tank}}^{t-1}$$

$$\left(1-\eta_{\text{loss}}\right)Q_{\text{tank}}^{t-1} - Q_{\text{tank}}^t \le H_{\text{tank}}^{\text{max}}$$

$$Q_{\text{tank}}^t - \left(1-\eta_{\text{loss}}\right)Q_{\text{tank}}^{t-1} \le H_{\text{tank}}^{\text{min}} \tag{10}$$

Where, Q_{tank}^t is the heat energy of heat storage tank in period t; $Q_{\text{tank}}^{\text{max}}$ is the storage capacity of heat storage tank; $H_{\text{tank}}^{\text{max}}$ and $H_{\text{tank}}^{\text{min}}$ are the maximum and minimum output power of heat storage tank respectively; η_{loss} is the loss rate of heat storage tank.

4. Peak shaving compensation algorithm

In order to give full play to the role of economic levers, maximize the effectiveness of limited resources, substantially reduce wind curtailment, and increase the acceptance rate of clean energy, the northeast power peaking shaving compensation management has been established. The core rules of the management approach are divided into: basic peak-shaving ancillary services and paid peak shaving ancillary services, and the latter mainly includes three options: unit operation peaking, peak load operation, cross-provincial peaking. To analyze the impact of the heat source operation on the profit of various units of the power system, this paper considers the auxiliary service compensation mechanism, and the detailed algorithm flowchart is shown as Figure 1.

In Figure 1, P is the power generation of each unit; α is the coefficient of the fine; M_{final} is the total amount of fine; Limit$_{\text{up}}$ is the upper limit of the fine; *Ele_price is* the compensation price; M_{sum} is the total amount of compensation.

The profit of each unit is that revenue from electricity sales minus coal consumption costs and minus M_{final} or add M_{sum}.

5. Case study

Simulation system derives from a city of Jilin province, northeast of China, which includes 6 CHP units, 4 CON units and a wind farm. 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 structure of the system is shown as Figure 2, which also shows the installed capacity of all units.
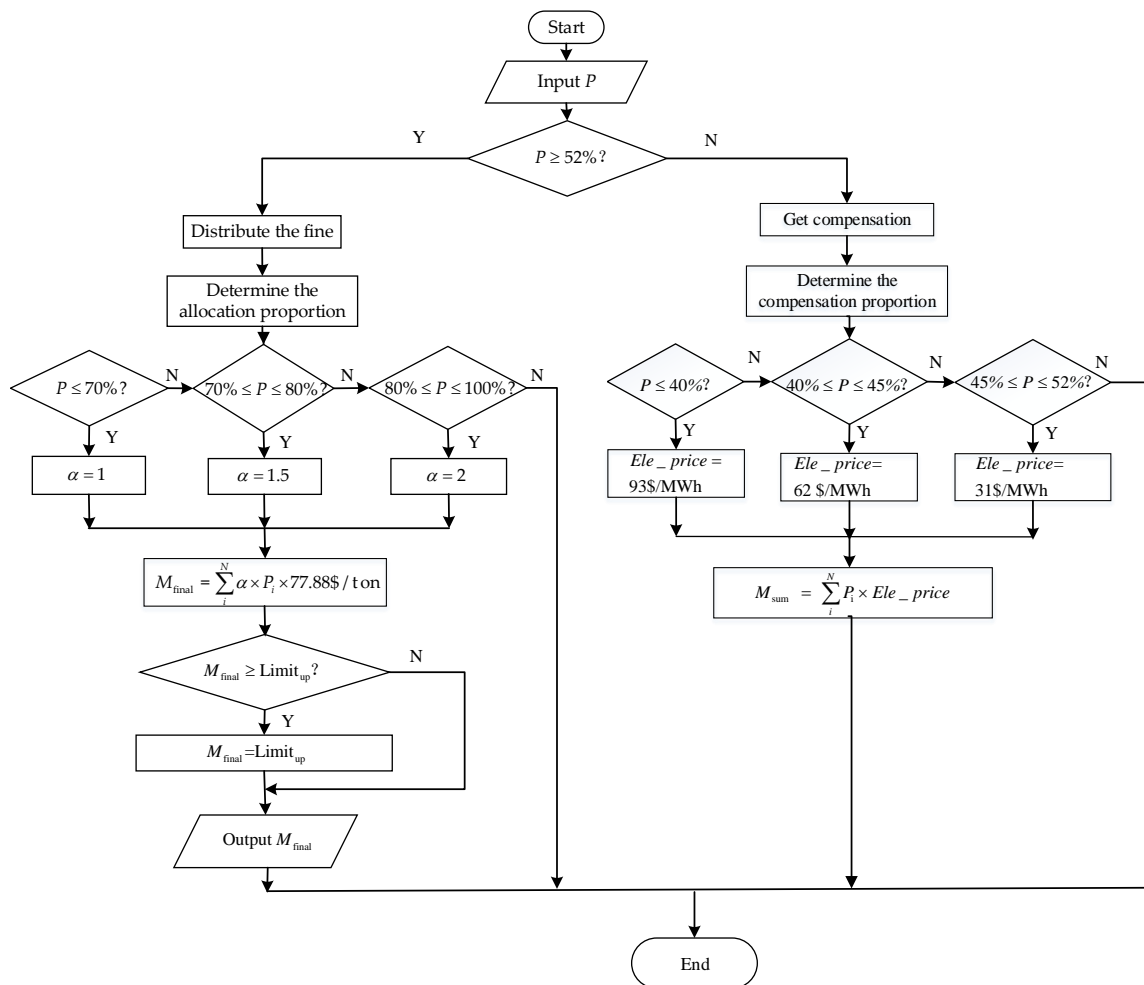
Figure 1. Flow chart for calculating the fine and compensation of each unit.
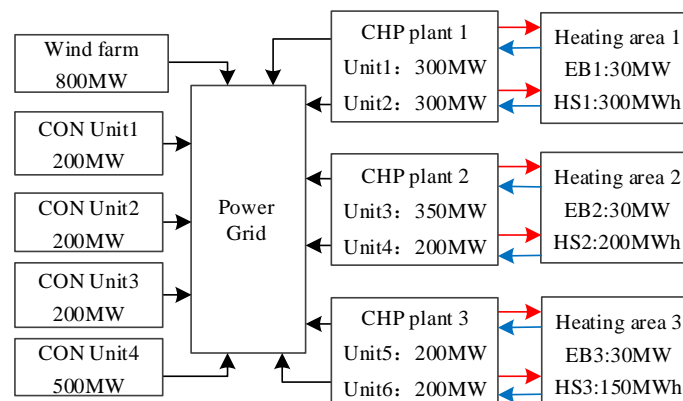
Figure 2. The sketch map of the simulation system.

Fitting parameters of coal consumption characteristic of CON units is shown as Table 1.

In this simulation system, the coal price is 77.88 \$/ton, generation price of the CHP units and CON units is 59.19 \$/MWh, and that of wind farm is 109.03 \$/MWh. As shown in Table 3, adding AHS to the system, the total profit of 6 CHP units and 4 CON units is \$ 1.7182×10^{8}, while without AHS, the total profit is \$ 1.7347×10^{8}. On the country, wind farm gains more with AHS.

Table 1. Coal consumption parameters of CON units.

CON	b_1	b_2	b_3
1,2,3	3.5	0.3	8.5×10^{-5}
4	4	0.3	6.5×10^{-5}

Fitting parameters of coal consumption characteristic of CHP units is shown as Table 2.

Table 2. Coal consumption parameters of CHP units.

CHP	a_1	a_2	a_3	a_4	a_5	a_6
1	0.75	0.27	7.6×10^{-5}	4.28×10^{-5}	1.14×10^{-4}	0.2037
2	0.75	0.27	7.6×10^{-5}	4.28×10^{-5}	1.14×10^{-4}	0.2037
3	0.75	0.27	7.6×10^{-5}	4.05×10^{-5}	1.14×10^{-4}	0.1719
4	0.75	0.27	7.1×10^{-5}	3.99×10^{-5}	1.08×10^{-4}	0.2029
5	0.75	0.27	7.1×10^{-5}	3.99×10^{-5}	1.06×10^{-4}	0.2029
6	0.75	0.27	7.1×10^{-5}	3.99×10^{-5}	1.06×10^{-4}	0.2029

Based on the simulation system, the profit of the whole heating season (145 days) of each unit both with and without AHS is obtained, as shown in Table 3.

Table 3. Profit of each unit.

Unit	With AHS/$	Without AHS/$
CHP 1	5.8858×10^{6}	5.7780×10^{6}
CHP 2	5.9674×10^{6}	5.8526×10^{6}
CHP 3	1.6687×10^{7}	1.6829×10^{7}
CHP 4	9.6481×10^{6}	9.8642×10^{6}
CHP 5	7.7650×10^{6}	7.9955×10^{6}
CHP 6	7.7358×10^{6}	7.6907×10^{6}
CON 1	3.2511×10^{7}	3.2958×10^{7}
CON 2	3.2441×10^{7}	3.2897×10^{7}
CON 3	3.9283×10^{7}	3.9790×10^{7}
CON 4	1.3898×10^{7}	1.3819×10^{7}
Wind farm	1.7671×10^{8}	1.5867×10^{8}

It can be concluded that if there is no compensation income, CHP units and CON units will face losses and wind farm will gain more profits. This will reduce the enthusiasm of thermal power plants to participate in the construction and operation of AHS. Therefore, after the AHS consuming wind power, it is necessary for the wind farm to compensate part of profits to the thermal power plants.

Figure 3 and Figure 4 show that adding AHS to the system can relieve the phenomenon of wind curtailment and promote wind farm to generate more power, however, CHP units and CON units face profit decline due to less power generation, especially in the evening.

Figure 3. Wind farm power generation on a typical day.

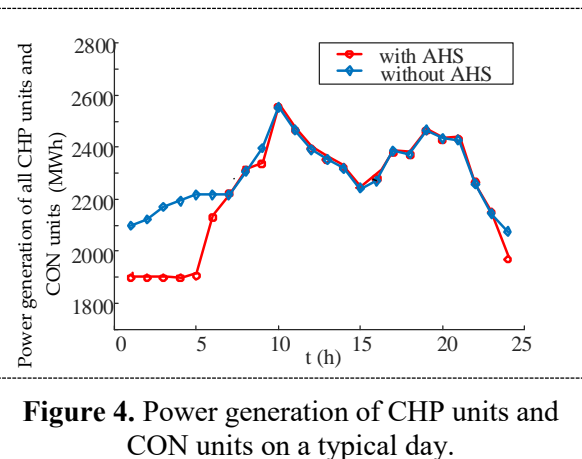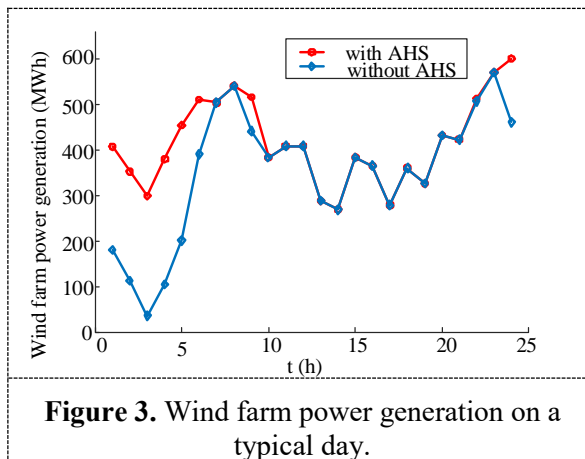**Figure 4.** Power generation of CHP units and CON units on a typical day.

Figure 5 shows the profit difference of CHP1 after adding AHS and before adding AHS. The profit difference increase with the rise of coal price. Adding AHS indicates that the required heat output of CHP units has been reduced, the amount of coal consumption will also decline. Therefore, when the coal price is higher, CHP units will be more willing to participate in the operation with AHS. The critical point of coal price is about 62.3$/ton.
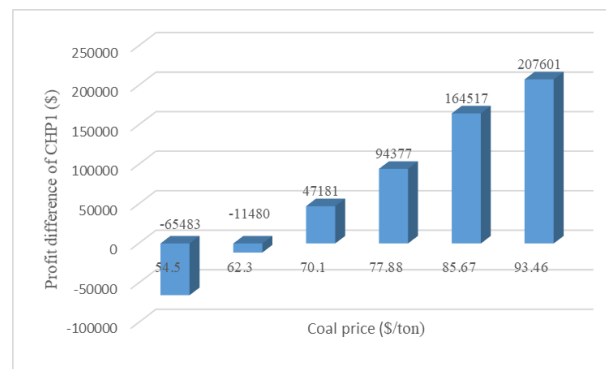
Figure 5. Profit difference of CHP1.

At last, we get the marginal curves of CHP units and wind farm and the average compensation price feasible region, as shown in Figure 6.
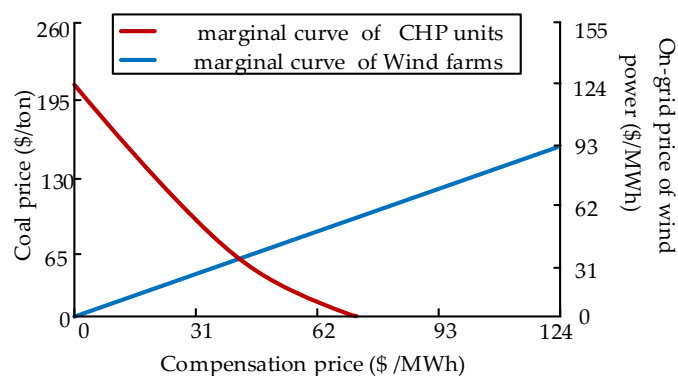
Figure 6. Feasible region analysis of the compensation price.

In Figure 6, the curve in red and blue color are the marginal curves of CHP units and wind farm. From this two marginal curves, we can conclude that with the increase of coal price, the expected minimum

compensation price of CHP units has decreased. And for wind farm, with the increase of on-grid price of wind power, the acceptable maximum compensation price also increases. The upper area between the two curves is the feasible region of the two parts.

6. Conclusions

In this paper, a production simulation model with AHS during heating season is established and the peak shaving compensation mechanism in northeast China is considered. Based on the model, the profits variation has been analyzed and we can get the following conclusions:

(1) With AHS configured, wind farm generates more power, while CHP units have reduced their power generation. So the wind farm gains more profits, CHP units face profit decline.

(2) When the coal price is higher, the CHP units will be more willing to participate in the operation with AHS and the critical point of coal price is nearly 62.3$/ton.

(3) Through the simulation study, the reasonable value of compensation price varies with wind power on-grid price and coal price. Besides, the feasible region of the compensation price is obtained, which have a guiding significance on the improvement of peak shaving compensation mechanism.

7. References

[1] Cho H, Smith AD, Mago P 2014 Combined cooling, heating and power: a review of performance improvement and optimization *Applied Energy* **136** 168-185.

[2] Wang J, Zhong H, Tan CW, et al. 2018 Economic Benefits of Integrating Solar-Powered Heat Pumps in a CHP System *IEEE Transactions on Sustainable Energy* 1.

[3] Wu C, Gu W, Jiang P, et al. 2017 Combined Economic Dispatch Considering the Time-Delay of a District Heating Network and Multi-Regional Indoor Temperature Control *IEEE Transactions on Sustainable Energy* 1.

[4] Fitzgerald N, Foley A M, Mckeogh E 2012 Integrating wind power using intelligent electric water heating *Energy* **48**(1) 135-43.

[5] Nielsen M G, Morales J M, Zugno M, et al. 2016 Economic valuation of heat pumps and electric boilers in the Danish energy system *Applied Energy* **167** 189-200.

[6] Rong S, Li Z, Li W 2015 Investigation of the Promotion of Wind Power Consumption Using the Thermal-Electric Decoupling Techniques *Energies* **8**(8) 8613-29.

[7] Rong S, Li W, Li Z, et al. 2015 Optimal Allocation of Thermal-Electric Decoupling Systems Based on the National Economy by an Improved Conjugate Gradient Method *Energies* **9**(1) 17.

[8] Chen X, Kang C, O'Malley M, et al. 2015 Increasing the Flexibility of Combined Heat and Power for Wind Power Integration in China: Modeling and Implications *IEEE Transactions on Power Systems* **30**(4) 1848-57.

[9] Christidis A, Koch C, Pottel L, et al. 2012 The contribution of heat storage to the profitable operation of combined heat and power plants in liberalized electricity markets *Energy* **41**(1):75-82.

[10] Liu D, Zhang G, Huang B, et al. 2016 Optimum Electric Boiler Capacity Configuration in a Regional Power Grid for a Wind Power Accommodation Scenario *Energies* **9**(3):144.