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Research on Benefit Equilibrium of Various Subjects in Regional Integrated Energy System

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Abstract. Regional integrated energy system is a combination designed to connect various energy supply and demand systems based on the in-depth integration of urban regional energy and information communication. With the integrated energy system in a certain industrial park as research object, the paper aims to determine energy constitutions within the integrated energy system and various load curves, calculate operating economic interests and users' energy consumption cost of various subjects under an independent node, analyze cooperation modes of these subjects in cooperation situations, discuss specific economic returns of such subjects under different combination modes and compare these combination modes, and rationally distribute the total returns of the integrated energy system by Shapley value method, based on which calculate the incremental economic benefits of various subjects.

1. Introduction

In recent years, with the continuous increase of energy demands and the gradual depletion of fossil energy, all the countries across the world are facing severe challenges resulting from energy problems. With the emerging of "internet +" concept, such development thinking as regional integrated energy system and energy internet have supplied new development concepts and routes for traditional energy industry [1-2]. The construction of regional integrated energy system will realize the flexible connection and full absorption of distributed energy with high penetration rate, support the collaborative optimization of more than one energy and improve the safety and efficiency of regional energy. Therefore, to attract all social parties to participate in the construction of regional integrated energy system and make the system sustainable, reproducible and propagable, it is necessary to research the construction, operation and business mode of regional integrated energy system [3-5].

At present, researches and practices in such fields as coordinated construction and operation of integrated energy system and win-win cooperation between diversified energy subjects are still at the initial stage internationally, thus making it deficient the systematic solution applicable to our national conditions and industrial development trends. Therefore, it is necessary to implement further research on such issues as the investment construction mode, integrated energy operation management mode and business mode featured by interactive participation and benefiting all participants of regional integrated energy system [6-8]. Distributed energy supply systems are mainly established in load center and, with the diversified development of distributed power generation forms, the business operation mode of distributed energy will also present diversified development in the future [9-10]. the paper focuses on analysing the business mode of distributed energy system with regional integrated energy system as practical implementation project, and also considers the operation characteristics of



various subjects in the integrated energy system and discusses their respective economic benefits in such links as transaction, cost input and value acquisition.

2. Operation modes of various subjects in the regional integrated energy system

Set up four categories of subjects in the regional integrated energy system, namely energy storage system, photovoltaic system, combined heat and power generation and users, calculate the benefits of such subjects under independent operation and cooperative operation according to their operation modes, and discuss the distribution of their interests under the cooperation mode as shown in Table 1.

Table 1. Operation modes of various subjects under independent and cooperation modes

Subjects	Independent mode	Cooperation mode
User (U)	Users purchase power from power grid and heat from municipality	Users acquire power preferentially from heat and power generation units, and then from photovoltaic system, energy storage system and power grid in succession until their power demands are satisfied.
Energy storage system (S)	Ensure the reliability of power supply without producing any direct economic benefit	Preferentially store excessive photovoltaic power output, charge itself in times of off-peak power price and supply power to users in non-charging time frame
Photovoltaic system (PV)	Have all power generated by PV system accessed to power grid	Have power generated by PV system preferentially used to supply power to users, and then charge stored energy, with the residual power accessed to power grid
Combined heat and power generation units (CHP)	Have all power generated by CHP units accessed to power grid and all CHP heat used for municipal heating by cost price	Have power generated by CHP units preferentially used to supply power to users, and then charge stored energy, with the residual power accessed to power grid

3. The benefit model of integrated energy system in different scenarios

3.1 Benefits model for various subjects under the independent mode

The operation diagram of various subjects under the independent mode is shown in Figure 1.

3.1.1 Operation benefits of users.

$$C_{U,I} = C_{U1,I} + C_{U2,I} \quad (1)$$

$$C_{U1,I} = \sum_{t=1}^T -(P_G \cdot Q_H) \quad (2)$$

$$C_{U2,I} = \sum_{t=1}^T -(P_L(t) \cdot L(t)) \quad (3)$$

Wherein, $C_{U,I}$ indicates the total operation benefits of users under the independent mode; $C_{U1,I}$ indicates daily heat energy consumption benefits of users; T indicates typical daily hours, determined as 24h; P_G indicates the price paid by users to purchase heat from municipal utilities; Q_H indicates users' total heat load within a day; $P_L(t)$ indicates the real-time power price at the time of t ; $L(t)$ indicates users' power load at the time of t .

3.1.2 Operation benefits of energy storage system.

$$C_{S,I} = 0 \tag{4}$$

Under the independent mode, energy storage system implements neither charging nor discharging, and thus produces little direct economic benefits.

3.1.3 Operation benefits of PV system

$$C_{PV,I} = \sum_{t=1}^T (P_{OG1} \cdot Q_{PV} + P_{PV} \cdot Q_{PV}) \tag{5}$$

Wherein, $C_{PV,I}$ indicates the operation benefits of PV system under the independent mode; P_{OG1} indicates power price in case that all PV power is accessed to power grid; Q_{PV} indicates total PV power generated at the time of t ; P_{PV} indicates feed-in tariff for PV power.

3.1.4 Operation benefits of combined heat and power generation (CHP) units

$$C_{CHP,I} = \sum_{t=1}^T (P_{OG2} \cdot Q_{GP}(t)) - C_{PC} \tag{6}$$

$$C_{PC,I} = \frac{1}{\eta_g(\beta+1)} P_{NG} \cdot Q_{NG} \tag{7}$$

$C_{CHP,I}$ indicates the operation benefits of CHP units under the independent mode; P_{OG2} indicates the price for access of power generated by CHP units to power grid; $Q_{GP}(t)$ indicates power generated at the time of t ; $C_{PC,I}$ indicates power generation cost of CHP units under the independent mode; in the model, power generation cost and heat generation cost are apportioned by heat-power ratio. η_g indicates air inflow efficiency of CHP units; β indicates heat-power ratio of the units; P_{NG} indicates gas price per cubic meter; Q_{NG} indicates the total amount of flue gas consumed by the units.

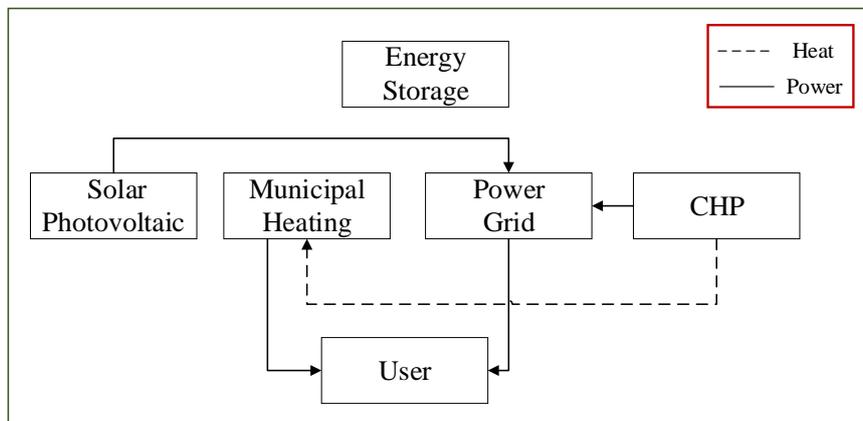


Figure 1. Operation diagram of various subjects under the independent mode

3.2 Benefits model for various subjects under the cooperation mode

The operation diagram of various subjects under the cooperation mode is shown in Figure 2.

3.2.1 Operation benefits of users

$$C_{U,C} = C_{U1,C} + C_{U2,C} \tag{8}$$

$$C_{U1,C} = \sum_{t=1}^T -(P_H \cdot Q_H) \tag{9}$$

$$C_{U2,C} = \sum_{t=1}^T -(P_L(t) \cdot L_G(t) + P_{CHP} \cdot L_{CHP}(t) + P_L(t) \cdot L_{PV}(t) + P_L(t) \cdot L_S(t)) \quad (10)$$

Wherein, $C_{U,C}$ indicates the total operation benefits of users under the cooperation mod; $C_{U1,C}$ indicates the daily benefits of users from heat purchase under the cooperation mode; $C_{U2,C}$ indicates the daily benefits of users from power purchase under the cooperation mode; T indicates typical daily hours, determined as 24h; P_H indicates the price for purchasing heat from CHP units by users; Q_H indicates the total heat load of users within a day; $P_L(t)$ indicates the real-time power price at the time of t ; $L_G(t)$ indicates the amount of power purchased by uses from power grid at the time of t ; $L_{CHP}(t)$ indicates the price of power directly purchased by users from CHP units; $L_{PV}(t)$ indicates the amount of power purchased by uses from CHP units at the time of t ; $L_S(t)$ indicates the amount of power purchased by uses from the energy storage system at the time of t .

3.2.2 Operation benefits of energy storage system

$$C_{S,C} = \sum_{t=1}^T (P_L(t) \cdot L_S(t) - P_L(t) \cdot L_{S,G}(t) - P_L(t) \cdot L_{S,PV}(t)) \quad (11)$$

$C_{S,C}$ indicates the operation benefits of energy storage system under the cooperation mode; $L_{S,G}$ indicates the amount of power purchased by energy storage system operator from power grid at the time of t ; $L_{S,PV}$ indicates the amount of power purchased by energy storage system operator from PV system at the time of t .

3.2.3 Operation benefits of PV system

$$C_{PV,C} = \sum_{t=1}^T (P_{PV} \cdot Q_{PV} + P_{OG1}(t) \cdot L_{G,PV}(t) + P_L(t) \cdot L_{PV}(t) + P_L(t) \cdot L_{S,PV}(t)) \quad (12)$$

$C_{PV,C}$ indicates the operation benefits of PV system under the cooperation mode; P_{OG1} indicates the price for the access of residual PV power to power grid; $L_{G,PV}(t)$ indicates the amount of PV power accessed to power grid at the time of t .

3.2.4 Operation benefits of CHP units

$$C_{CHP} = \sum_{t=1}^T (P_{CHP} \cdot L_{CHP}(t) + P_H \cdot Q_H - C_{PC,C}) \quad (13)$$

C_{CHP} indicates the operation benefits of CHP units under the cooperation mode, and $C_{PC,C}$ indicates the operation cost of the units. In the cooperation mode, the operation cost includes both power and heat generation cots.

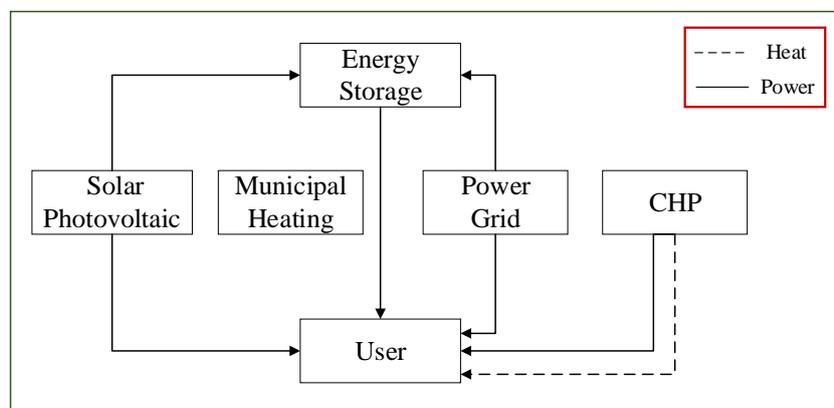


Figure 2. Operation diagram of various subjects under the cooperation mode

4. Case study

Select a certain industrial park as research object for the analysis and calculation of the benefits of various subjects respectively under the independent mode and cooperation mode. Supposing that the industrial park locates at Northern China with heating load in winter, select the power curves of electricity and heat load in typical winter days as basic data (as is shown in Figure 3). PV generated power is shown in Figure 4, from which we can see that as the power generation of PV system is unstable to a large degree, during the operation time frame 13:00-17:00, the amount of its power output is larger than users' power load, while at other time frames of the day, the amount of its power output is smaller than users' power load, and at night, the amount is 0.

In the case analysis, suppose the price for access of all PV power to power grid is 0.75 yuan / (kW·h), that for access of residual PV power to power grid is 0.4 yuan / (kW·h), and that for power directly supplied by PV system is 0.8 yuan / (kW·h). Local time-of-use power price data can be seen in Table 2, and the price for power directly supplied by CHP units can be seen in Table 3.

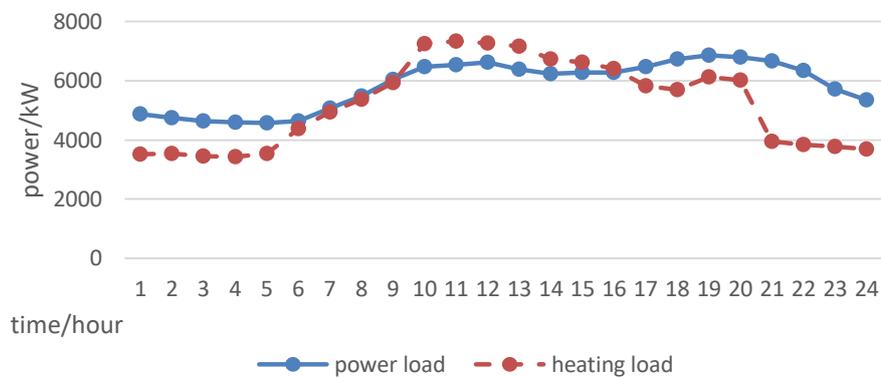


Figure 3. Curve of Users' load in typical winter days

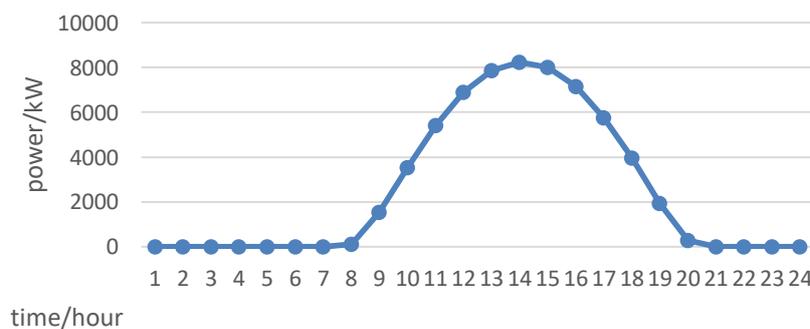


Figure 4. Curve of PV power output in typical winter days

Table 2. Time-of-use power price for power sales from power grid

Time frame	Power price(yuan / kW h)
0:00-8:00	0.54
8:00-14:00 17:00-19:00 22:00-24:00	0.82
14:00-17:00 19:00-22:00	1.15

Table 3. Price of power directly traded by CHP units

Time frame	Power price(yuan / kW h)
0:00-8:00	0.56
8:00-14:00 17:00-19:00 22:00-24:00	0.67
14:00-17:00 19:00-22:00	1.04

Benefits calculated respectively under independent and cooperation modes are shown in Table 4, from which it can be seen that the total benefits of various subjects increase by 43,760 yuan under cooperation mode. As users need to purchase power and heat energy to satisfy their demands, the benefit of users remains negative. Power energy is required to be purchased from power grid in case that domestic power supply within the system is insufficient, and then the total benefit will also be negative.

Table 4. Results comparison of benefits of integrated energy system under two modes

Total benefit under the independent mode (10,000 yuan)	Total benefit under the cooperation mode (10,000 yuan)	Incremental Benefits (10,000 yuan)
-7.301	-2.926	4.376

Distribute the increment of benefits by Shapley value method, and specific benefits distribution of four subjects are respectively shown in Table 5:

It can be seen from calculation results that under the cooperation mode, the heat or power consumption cost of users reduces, and the benefits of other subjects all increase. Therefore, the subjects within the system can achieve the reduction of their operation cost and increase of benefits through directly implementing power and heat transactions.

Table 5. Final benefits acquired based on calculation by Shapley value method

	U (10,000 yuan)	S (10,000 yuan)	PV (10,000 yuan)	CHP (10,000 yuan)
Benefits acquired under the independent mode	-15.400	0	7.172	0.781
Benefits distribution by Shapley value method	2.371	0.817	0.170	1.107
Final benefits	-13.029	0.817	7.342	1.888

It can be concluded from the above calculation results that the benefits of all the subjects under the cooperation mode are larger than under the independent mode, and the total benefits acquired under the cooperation mode exceed those under the independent mode by 8,000 yuan. In cooperation mode situation, the benefits of various subjects are distributed by Shapley value method, and corresponding calculation results show that users' energy consumption cost may reduce by 23,710 yuan; energy storage system may acquire benefits worth 8,170 yuan; PV system may acquire benefits worth 73,420 yuan, increasing by 1,700 yuan compared with the independent mode; CHP system may acquire benefits worth 18,888 yuan, increasing by 11,070 yuan compared with the independent mode. Therefore, the operators of regional integrated energy system should adopt the mode of cooperative energy supply to acquire more benefits.

5. Conclusion

The key of the sustainable development of regional integrated energy system is the profit model and the profit distribution. As the policy of the commercial operation of the integrated energy system is still not clear, cooperative game theory can be used to research a feasible cooperation pattern. Based on an industrial park in the north of China, with the energy structure and the user load situation, the

paper measured the efficiency of the different body when they at independence or cooperation mode. By measuring, the system revenue at the cooperation mode is greater than the sum of each subject gains at the independence mode. At the cooperation mode, the cost of user is smaller. In addition, based on the contribution principle of the Shapley value method to divide the system revenue at the cooperation mode, the economic benefits of each subject is greater than the independence mode.

Acknowledgments

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