Optimal scheduling of multi-park integrated energy system under renewable energy quota considering demand side response

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Abstract. The integrated energy system (RIs) is composed of electricity/gas/cold/heat and other energy sources, which can realize the coordinated utilization of different forms of energy. RIs is conducive to promoting the rational utilization of clean energy, and the mutual coupling between different energy sources can effectively improve the overall energy utilization efficiency and operation economy of the system. The diversity of energy supply and demand makes the system operation complex and diverse, so it is indispensable to optimize the system operation scheduling. Demand response is an effective means to optimize the multi-objective scheduling of regional comprehensive energy system. RPS and green certificate trading mechanism are new methods to promote the consumption of renewable energy. In the process of green certificate trading, considering the load side demand response is conducive to realizing the maximum utilization of renewable energy power generation and improving the absorption rate of renewable energy power generation.

1. Introduction

1.1. Renewable resources quota system and green license trading

Renewable energy quota system means that the government adjusts the market share of renewable energy generation to improve the utilization rate of renewable energy through compulsory means such as law. Green certificates certifying that electricity comes from renewable sources represent a certain amount of green electricity that can be traded on the market and are issued by the government to power generation companies [1]. Quotation system is an important supporting system. The subject of quota obligation can purchase green certificate from the power generation enterprise to prove the completion of quota target. Compared with the fixed electricity price system which provides fixed subsidies through administrative means, green card trading mainly provides additional income for renewable energy through market means. Its price is formed by market, which is conducive to promoting the technological progress and cost reduction of renewable energy. The calculation formula for the number of green certificates available to power generation enterprises can be expressed as Equation (1):

\[ = Ps\Delta t/1000 \]

(1)
Where, \( G \) is the number of green certificates participating in the transaction (unit is \( 1 \) this certificate / \( (\text{MW} \cdot \text{h}) \)); \( P_s \) is the actual output of the \( s \)-th renewable energy power generation equipment (unit is kW); \( \Delta t \) is the duration of the scheduling period (unit is h).

The purpose of introducing green card trading is to make the way of quota holders to fulfill quota more flexible and to promote the technological progress of renewable energy through market price discovery. Due to the fluctuation of renewable energy resources and the unbalanced development among regions, the quota system is an administrative means with single assessment standard and strong compulsion. The introduction of marketized transaction can provide diversified choices for the subject of quota obligations to fulfill the quota. Renewable resources quota system and green license trading are important means to promote the healthy development of renewable energy and improve the absorption capacity of renewable energy. This means can effectively guarantee the development of the renewable energy market, and the phenomenon of wind and electricity abandonment will be further alleviated.

1.2. Demand response

Regional Integrated Energy System (RIES) is usually composed of various forms of energy such as electricity, gas, cold and heat. Coupling between different energy sources can effectively improve the overall energy utilization efficiency and operating economy of the system. Electric and thermal combined demand response is an effective means of multi-objective optimization scheduling for regional integrated energy system.

The optimal dispatching of regional comprehensive energy system should take into account both economic efficiency and energy utilization efficiency. As an important means of regulation and control of regional comprehensive energy system, the combined demand response resources of electricity and heat are beneficial to the optimal energy allocation and dispatching of regional comprehensive energy system.

The incentive power demand response cost model is the economic compensation of the users participating in the demand response, which is determined by the demand response agreement. This cost model is usually a quadratic function, as shown in Equations (2) and (3):

\[
C_{dr,i}(t) = a_{dr,i}P_{dr,i}^2(t) + b_{dr,i}P_{dr,i}(t) \\
P_{dr,i,min}(t) \leq P_{dr,i}(t) \leq P_{dr,i,max}(t)
\]

Where: \( C_{dr,i}(t) \) represents the demand response cost of the \( i \)-th incentive demand response cluster users in the \( t \)-period; \( P_{dr,i}(t) \) represents the demand response reduction power of the \( i \)-th incentive demand response cluster users at the time period \( t \); \( a_{dr,i} \) represents the quadratic coefficient of the \( i \)-th incentive demand response user compensation amount; \( b_{dr,i} \) represents the first order coefficient of the \( i \)-th incentive demand response user compensation amount. \( P_{dr,i,max}(t) \) and \( P_{dr,i,min}(t) \) respectively represent the upper and lower limits of the \( i \)-th cluster user's demand response capability in the time period \( t \).

2. The optimization model

2.1. The objective function

The multi-park integrated energy system, namely the regional integrated energy system [3], can be regarded as several subsystems due to the geographical distribution of renewable resources, which are connected by the regional large power grid and the regional natural gas network. Optimal scheduling of multi-park comprehensive energy system should aim at the optimal operation index of the whole comprehensive energy system. As shown in Equation (4), the optimal operation economy of the whole system should be taken as the objective function for the optimization of multi-park comprehensive energy system considering demand side response, renewable energy quota system and green card transaction:

\[
C = C_e + C_{gas} + C_{dr} - C_{gre}
\]
In the formula, $C_e$ is the electricity purchase cost of the park, $C_{gas}$ is the gas purchase cost of the park, $C_{dr}$ is the cost generated by reducing the load of the park, and $C_{gre}$ is the income from green license transaction. Electricity purchase cost, gas purchase cost, load reduction cost and green card transaction income are respectively shown in Formula (5) to (8):

$$C_e = \sum_{i=1}^{m} \sum_{j=1}^{n} P_{\text{Grid},i} \Delta t$$  \hspace{1cm} (5)

$$C_e = \text{Pri}_e \sum_{i=1}^{m} \sum_{j=1}^{n} \left( \frac{P_{\text{MT},i}}{\eta_{\text{MT},i}} + \frac{Q_{\text{GB},j}}{\eta_{\text{GB},j}} \right) \Delta t$$  \hspace{1cm} (6)

$$C_{dr} = \sum_{i=1}^{m} \sum_{j=1}^{n} \left( a*P_{e,i-DR}^2 + b*P_{h,j-DR}^2 \right) \Delta t$$ \hspace{1cm} (7)

$$C_{gre} = C_{gre-buy} - C_{gre-sell} = \text{Pri}_{gre} \sum_{i=1}^{m} \sum_{j=1}^{n} \left( \text{i,t-sell} - \text{i,t-buy} \right) \Delta t$$  \hspace{1cm} (8)

Where $\text{Pri}_e$ is the price of unit caloric value of natural gas purchased, $P_{\text{MT},i}$ and $Q_{\text{GB},j}$ are respectively the generation power of MT and heat generation power of GB in the ith IES at time $t$; $\eta_{\text{MT}}$ and $\eta_{\text{GB}}$ correspond to the working efficiency of equipment respectively. $C_{dr}$ Represents the economic cost of encouraging users to participate in load demand response. Where $\text{Pri}_{gre}$ represents the transaction price of a single green card, and $\text{i,t-sell}$ and $\text{i,t-buy}$ represent the number of green cards sold and bought by the ith IES system at the time $t$, respectively.

2.2. The constraint

2.2.1. Power balance constraint: Electrical and thermal power constraints of system operation are shown in Equations (9) and (10):

$$P_{\text{GT}(L,t)} + P_{\text{WP}(L,t)} + P_{\text{PV}(L,t)} + P_{\text{Grid}(L,t)} + P_{\text{ES-dis}(L,t)} - P_{\text{ES-ch}(L,t)} = L_e(L,t)$$  \hspace{1cm} (9)

$$Q_{\text{GB}(L,t)} + Q_{\text{HX}(L,t)} = L_h(L,t)$$  \hspace{1cm} (10)

Where $P_{\text{GT}(L,t)}, P_{\text{WP}(L,t)}, P_{\text{PV}(L,t)}, P_{\text{ES-dis}(L,t)}, P_{\text{ES-ch}(L,t)}$ and $L_e(L,t)$ are respectively the gas turbine output, wind power output, Photovoltaic power output, discharge power of energy storage equipment, charging power of energy storage equipment and the Internal electrical load of the ith IES. $P_{\text{Grid}(L,t)}$ is the energy exchanged with the external Grid at time $t$ of the ith IES. $Q_{\text{GB}(L,t)}$ and $Q_{\text{HX}(L,t)}$ are respectively the heat generated by the waste heat boiler and heat exchanger of the ith IES at time $t$, and $L_h(L,t)$ is the heat demand of the ith IES at time $t$.

2.2.2. Equipment output constraint: Upper and lower wind turbine power constraints, lower bound constraint conditions on photovoltaic power generating equipment, lower limit on gas turbine power constraints, constraint conditions, the heat generated by the upper and lower limits of the heat exchanger heat exchanger heat balance constraints, gas boiler, the heat generated by the upper and lower limits on the purchase of electricity from the grid floor constraint conditions such as type (11) to type respectively (17):

$$0 \leq P_{\text{WP},i} \leq P_{\text{WP},i-\text{max}}$$  \hspace{1cm} (11)

$$0 \leq P_{\text{PV},i} \leq P_{\text{WP},i-\text{max}}$$  \hspace{1cm} (12)

$$0 \leq P_{\text{GT},i} \leq P_{\text{GT},i-\text{max}}$$  \hspace{1cm} (13)

$$0 \leq Q_{\text{HX},i} \leq Q_{\text{HX},i-\text{max}}$$  \hspace{1cm} (14)

$$Q_{\text{HX}} = c * P_{\text{GT}}$$  \hspace{1cm} (15)

$$0 \leq Q_{\text{GB},i} \leq Q_{\text{GB},i-\text{max}}$$  \hspace{1cm} (16)

$$0 \leq P_{\text{Grid},i} \leq P_{\text{Grid},i-\text{max}}$$  \hspace{1cm} (17)

Among them, the electro - heat ratio parameters of C type gas turbine.

2.2.3. Constraint conditions of electric energy storage equipment: In integrated energy system, the output of the wind power and photovoltaic power generation is highly affected by the natural factors,
congenital deficiencies, output power instability and intermittent, the configuration of electric energy storage can improve the reliability of power supply, reduce a lot of give up wind power and photovoltaic power phenomenon, give full play to the advantages of using renewable energy to generate power. At present, the widely used electric energy storage equipment is the battery, whose chemical process is reversible. It converts electric energy into chemical energy when charging and chemical energy into electric energy when discharging. According to the different running state, the whole working process of the battery can be divided into charging process, discharging process and only storing electric energy process. The charging and discharging processes of the battery are shown in Equations (18) and (19) respectively:

\[ S(i, t) = (1 - \delta_e) S(t - 1) + P_{in} \Delta t \eta_{in}^e / E_{BD}^N \]  
\[ S(i, t) = (1 - \delta_e) S(t - 1) + P_{out} \Delta t / (\eta_{out}^e \cdot E_{BD}^N) \]

Where: \( \delta_e \) is the power consumption rate of the battery itself, %/h; \( P_{in} \) is the power stored in the battery, kW; \( P_{out} \) is the electric energy release power of the battery, kW; \( S(t) \) is the capacity of the battery after the t time period; \( S(t-1) \) is the remaining electric quantity of the battery after the period t - 1; \( \eta_{in}^e \) is the rated storage efficiency of the battery; \( \eta_{out}^e \) is the rated energy release efficiency of the battery; \( E_{BD}^N \) is the rated capacity of the battery, kW/h.

2.2.4. IES electric heating load demand response constraints: Electrical power balance constraints, thermal power balance constraints and load size limit conditions that can participate in the demand response are shown in Equations (20) to (23):

\[ L_{e,i} = L_{e0,i} + P_{e,i-DR} \]  
\[ L_{h,i} = L_{h0,i} + P_{h,i-DR} \]  
\[ 0 \leq P_{e,i-DR} \leq 0.2 \cdot L_{e0,i} \]  
\[ 0 \leq P_{h,i-DR} \leq 0.2 \cdot L_{h0,i} \]

\( L_{e,i} \) is the electric power after demand response, \( L_{e0} \) is the electric load before load demand response, and \( P_{e,i-DR} \) is the translational electric power of the ith IES. \( L_{h,i} \) is the thermal power after demand response, \( L_{h0,i} \) is the thermal load before load demand response, and \( P_{h-DR} \) is the translational thermal power of the ith IES.

2.2.5. Quota constraint of green certificate: Quota restrictions for green certificates are shown in Equations (24) and (25):

\[ (i,t)_{Ren} + (i,t)_{buy} - (i,t)_{sell} = \lambda_i \cdot P_{(i,t)} / 1000 \]  
\[ (i,t)_{Ren} = (P_{WP(i,t)} + P_{PV(i,t)}) / 1000 \]

In the formula, \( (i,t)_{Ren} \) represents the amount of green certificates that can be converted for electricity generated by renewable resources wind and light within IES I, and \( \lambda_i \) is the renewable energy quota of IES I.

3. Example and analysis:

3.1. Example setting

In this paper, an example from selected from three different renewable resources of the park area of integrated energy system, through the MATLAB modeling and solving, zone 1 and zone 3 are wind power and photovoltaic access, including 1 park of wind resources and light resource is very abundant, its renewable energy power generation is bigger, park 2 photovoltaic wind resources are scarce, only access. In this paper, the price of the green card is 100 yuan per copy.
3.2. Running results
The respective demands for electric energy and heat energy of the three parks are shown in Figure 1 and Figure 3 below. Figure 2 shows the respective supply of electric energy of the three parks. Fig. 4 and Fig. 5 respectively show the demand response results of the three parks considering the electric load and heat load side of the park respectively. Figure 6 shows the green certificate trading results of the three parks.

![Figure 1. Basic demand of electric power in three parks](image1)

![Figure 2. Electricity supply of the three parks](image2)

![Figure 3. Thermal power demand of the three parks](image3)

![Figure 4. Electrical power response of the load side of the three parks](image4)

![Figure 5. Demand response results of the three parks considering the electric load](image5)

![Figure 6. Green certificate trading results of the three parks](image6)
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Figure 5. Electrical power response of the load side of the three parks

Figure 6. Green certificate transactions in the three parks

3.3. Conclusion
Each zone of the location and area of different size, different wind and light conditions, thus it can be obtained from renewable resource power clean electricity is different also, much of the park's residents industrial load, load, different living habits and so on makes the park, the demand for electricity and heat energy is different, so that the relationship between supply and demand and the tension inside the park are different. For example, the park 2 electricity load and thermal load is larger than that of zone 1 and zone 3, it is more demand for electricity and heat, but the figure 2 (b) we can know its renewable resource conditions than other two park, park 2 a good portion of electricity is through the grid from the outside world and within the gas turbine, only by solar panels during the day can get clean electricity. Compared with Park 2, Park 1 and Park 3 have much better natural resource conditions and less demand for electric energy and heat energy. Their clean electric energy can be sold to other parks through large power grid, so that parks like Park 2 can purchase this part of clean electric energy for use. This is the green card transaction, which enables the park with rich natural resources to sell the remaining clean electric energy after meeting its own electricity demand, which can not only obtain additional economic sources but also improve the utilization rate of wind energy. This is a manifestation of sustainable and scientific development.

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