Optimal Scheduling of Park Integrated Energy System Based on Multi-energy Complementary

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Abstract. For the park level integrated energy system with renewable energy access, in order to optimize the operation cost of the park and solve the problem of renewable energy consumption, this paper proposes a day ahead optimized scheduling model of the park integrated energy system, which provides an effective solution for renewable energy consumption by considering the coordination of energy conversion and energy storage equipment to achieve multi-energy complementarity. Finally, an example is given to verify the validity and feasibility of the proposed model.

1. Introduction

The integrated energy system (IES), through a large number of energy conversion equipment, centralized management and centralized distribution of various energy forms, including solar, wind and other renewable energy, plays an important role in alleviating the global energy crisis and reducing environmental pollution problems, and its also the effective measures for the unbalanced distribution of energy resources. Regional integrated energy system (RIES) is located in the user side, which is one of the important forms of IES. Among them, the industrial park has become the main application of RIES by coordinating the conversion process of multi units and multi energy in the park, coupling the power, heat and gas systems, meeting the different load demand in the park, and promoting the local consumption of renewable energy.

In the research of RIES scheduling model, a multi energy optimal scheduling model considering the coordination of electric storage, distributed energy access and load side demand response was given in [1]; a coordinated scheduling method considering the initiative of unit peak load regulation was given in [2]; in [3], establishes a thermal system energy flow model with power coordination, and establishes an optimal scheduling considering the constraints of heat exchange links. In [4], a two-stage scheduling method combining multi-objective optimization and comprehensive decision-making is proposed for the economic emission scheduling of cogeneration.

This paper establishes the optimal scheduling model of the integrated energy system of the park, and considers the cooperation of multi-energy conversion equipment and energy storage devices in the park to provide solutions for the consumption of renewable energy, and introduces load-side demand response and time of use electricity price cooperation. Increase or decrease the load according to price, reduce the cost of energy purchase, and increase the additional income. Due to the model is a mixed integer programming model that is more difficult to solve, so linearizing some models to become a linear programming solving by CPLEX. Finally, by setting a variety of scheduling schemes in the calculation
example, gradually adding energy conversion equipment, energy storage equipment and demand response, by comparing the park scheduling costs and renewable energy consumption under each scheme to verify the effectiveness of the proposed model.

2. Structure framework and model of park’s integrated energy system

2.1. Overview of park’s IES

The park’s integrated energy system in this paper is composed of three parts: the energy input side, the energy conversion system and the load side; the energy input side includes the power grid, gas network and renewable energy access. The internal energy conversion system mainly includes power to gas (P2G), gas turbine (GT), combined heat and power (CHP), electric boiler (EB), and energy storage equipment, they cooperate to completes the conversion between different energy sources according to the output characteristics of renewable energy, time-of-use electricity prices and response demand of the load; the load side is composed of electricity, gas and thermal.

![Figure 1 Structure of the park’s integrated energy system](image)

2.2. Objective Function

In the multi-energy complementary integrated energy system of the park, the lowest dispatching cost is the goal. The cost includes the purchase cost of the energy network, the start-up and shutdown costs of the units in the park, the penalty costs of wind and solar. At the same time, in coordination with the load-side demand response, various types of equipment in the park are flexibly dispatched to increase the revenue from selling electricity to the power grid, so that the total operating cost of the park is the lowest.

\[
F = \min \sum_{t=1}^{N_t} \left( F_t^{in} + \frac{q_{sk}}{t} + F_t^{loss} - F_t^{out} - F_t^{dr} \right)
\]

Where \( F_t^{in} \) is the energy purchase cost of period \( t \); \( F_t^{q/s,k} \) is the start and stop cost of controllable unit \( k \) of period \( t \); \( F_t^{loss} \) is the penalty cost of period \( t \); \( F_t^{out} \) is the energy sale income of period \( t \); \( F_t^{dr} \) is the compensation cost of load side demand response; \( N_t \) is the number of scheduling periods.

2.3. Base-Case Constraints

2.3.1. System balance constraints. In the dispatching operation of the park, balance constraints are set for different energy forms, power balance, natural gas balance and thermal balance constraints.

\[
P_t^{in} + P_t^{WT} + P_t^{PV} + P_t^{CHP} + P_t^{GT} = P_t^{LDR} + P_t^{P2G} + P_t^{EB} + P_t^{out}
\]
considering the demand response; $P_t^{P2G}$, $P_t^{EB}$ represent the power consumption of P2G, EB; $P_t^{out}$ is the selling power;

(2) Natural gas balance constraints

$$G_t^{in} + G_t^{P2G} = G_t^{CHP} + G_t^{GT} + G_t^{GS} / \eta_{GS}$$  

(3)

Where $G_t^{in}$ is the gas purchase cost; $G_t^{P2G}$ is the output of P2G; $G_t^{CHP}, G_t^{GT}$ is the gas consumption of CHP, GT; $G_t^{GS}$ is the power of gas storage to store; $\eta_{GS}$ is the efficiency of the gas storage;

(3) Thermal balance constraint

$$\eta_{heat} \left( H_t^{CHP} + H_t^{EB} - H_t^{HS} / \eta_{HS} \right) = H_t^{LDR}$$  

(4)

Where $H_t^{CHP}, H_t^{EB}$ is the output of CHP,EB; $H_t^{GS}$ is the power of thermal storage to store heat; $\eta_{HS}$ is the efficiency of the heat storage; $\eta_{heat}$ is the heat utilization ratio of network; $H_t^{LDR}$ is the heat load after considering the demand response;

2.3.2. Unit inequality constraints

(1) Minimum up or down time constraints

$$\left( U_{t-1}^k - U_t^k \right) \left( T_{t-1}^k \right) \geq 0$$  

(5)

$$\left( U_t^k - U_{t-1}^k \right) \left( T_{t-1}^k \right) \geq 0$$  

(6)

Where $U_{t-1}^k, U_t^k$ represent the start-stop status of the unit k at t-1 and t; 0 is shutdown state, 1 is start-up state; $T_{t-1}^k$ is the continuous start-up time of unit k before the shutdown time, $T_t^{k,off}$ is the minimum continuous startup time required by unit k; the same with down time constraints;

(2) Climbing power constraint

$$r_d \Delta t \leq P_t^k - P_{t-1}^k \leq r_u \Delta t$$  

(7)

Where $r_d, r_u$ represent the rate of power climbing of unit k; $P_t^k$ is the output of the unit k at time t;

(3) Output constraint

$$U_t^k P_{t,min}^k \leq P_t^k \leq P_{t,max}^k U_t^k$$  

(8)

Where $U_t^k$ is the start-stop status of the unit k; $P_{t,min}, P_{t,max}$ represent the minimum or maximum output of unit k;

2.4. Unit mathematical model

(1) Power to gas unit

$$G_t^{P2G} = \eta_{P2G} P_t^{P2G}$$  

(9)

Where $\eta_{P2G}$ is the conversion efficiency of P2G;

(2) Gas turbine unit

$$G_t^{GT} = \left[ F(P_t^{GT}) + G_t^{q,GT} + G_t^{s,GT} \right] / L_{H,ANG}$$  

$$F(P_t^{GT}) = a_q + b_q P_t^{GT} + c_q (P_t^{GT})^2$$  

(10)

(11)

Where $F(P_t^{GT})$ is the Heat rate curve of GT; $G_t^{q,GT}, G_t^{s,GT}$ is the consumption of GT; $a,b,c$ is the Gas factor of GT; $L_{H,ANG}$ is the high calorific value of natural gas;

(3) Electric boiler unit

$$H_t^{EB} = \eta_{EB} P_t^{EB}$$  

(12)

Where $\eta_{EB}$ is the conversion efficiency of EB;
(4) Combined heat and power unit
\[ P_{t}^{CHP} = G_{t}^{CHP} \eta_{MT}^{t} L_{HANG} \]  
\[ H_{t}^{CHP} = G_{t}^{CHP} (1 - \eta_{MT}^{t} - \eta^{t}) L_{HANG} \]  
where \( \eta_{MT}^{t} \) is the conversion efficiency of Micro gas turbine; \( \eta^{t} \) is the heat loss rate;

(5) Energy storage
Energy storage equipment including heat storage and gas storage.
\[ C_{t}^{S} = (1 - \eta_{CS}^{t}) C_{t-1}^{S} + G_{t}^{S} \Delta t \]  
\[ G_{t}^{S, \min} \leq G_{t}^{S} \leq G_{t}^{S, \max} \]  
\[ C_{t}^{S, \min} \leq C_{t}^{S} \leq C_{t}^{S, \max} \]  
Where \( C_{t}^{S}, C_{t-1}^{S} \) is the energy storage capacity at time \( t \) and \( t-1 \); \( G_{t}^{S} \) is the energy storage power of period \( t \); \( G_{t}^{S, \min}, G_{t}^{S, \max} \) represent the minimum or maximum operating power of unit \( k \);

2.5. Demand side management
Load side participation in demand response is the most important forms of demand side management; The demand management system divides the load involved in the response into two types: shift able load and load reduction according to the level of load and electricity consumption time;  
\[ P_{t}^{DR} = P_{t}^{DR, \text{cut}} + P_{t}^{DR, \text{shift}} \]  
where \( P_{t}^{DR} \) is the load participated in demand response; \( P_{t}^{DR, \text{cut}}, P_{t}^{DR, \text{shift}} \) represent the load reduction and shift able load; 
(1) Load reduction
\[ 0 \leq P_{t}^{DR, \text{cut}} \leq \alpha_{t}^{p, \text{cut}} \bar{P}_{t}^{LD} \]  
where \( \alpha_{t}^{p, \text{cut}} \) is the maximum ratio of load reduction; \( \bar{P}_{t}^{LD} \) is the power load forecast;  
(2) Shift-able load
For the load that can be suspended in the park, it can be translated according to the park scheduling plan, and in a scheduling cycle, the sum of the translated in and translated out load should be 0.
\[ P_{t}^{DR, \text{shift}} \leq \alpha_{t}^{p, \text{shift}} \bar{P}_{t}^{LD} \]  
where \( \alpha_{t}^{p, \text{shift}} \) is the maximum ratio of shift able load;
For the demand side responsive power load, the sum of the maximum load in the current period and the load participating in the demand side response must be less than the maximum value of the electric load prediction at that time, otherwise the phenomenon of load loss will occur:
\[ P_{t}^{DR, \text{shift}} \leq \alpha_{t}^{p, \text{shift}} \bar{P}_{t}^{LD} \]  

3. Case Study
The park’s integrated energy system established in this paper includes three parts: superior energy access, internal energy conversion units and load side. Superior energy access includes purchasing energy from superior network and renewable energy access; internal energy conversion unit includes four kinds of energy: GT, CHP, EB, P2G and two kinds of energy storage devices: heat storage and gas storage; 
Due to the large amount of wind and solar abandoned in winter, and the large amount of heat load demand in the park, when the CHP unit outputs to supply heat load, the demand for power load is reduced, the consumption of renewable energy will be more difficult. Therefore, the prediction curves of typical winter days of the multi energy integrated system in the park are as follows:
In order to verify the impact of the cooperation of different units, time-of-use price and load-side demand response in the park dispatch, four scheduling schemes were set up, scheme 1 to 4 add different units and demand response in the system.

| Scheme | Add heat storage | Add P2G and gas storage | Add demand response |
|--------|------------------|-------------------------|---------------------|
| 1      | ×                | ×                       | ×                   |
| 2      | √                | ×                       | ×                   |
| 3      | √                | √                       | ×                   |
| 4      | √                | √                       | √                   |

3.1. Park’s multi-energy complementation and cooperation of units
The cooperation between multi units in the park provides a solution for multi-energy access and the consumption of new energy. Analysis of the cooperative output of each device under Scheme 4 and the balance of electricity, natural gas and heat:

In the winter, park’s IES have heat load demand all day. There is no heat storage equipment in scheme 1, and the EB will run 24 hours to provide heat energy. Therefore, the park will purchase a large amount of electricity in the park;

In scheme 4, all energy conversion units cooperates with the energy storage equipment. At the lower electricity price (23:00-07:00), park’s power load provided by the power grid and renewable energy. On this basis, the unconsumable electric energy can be converted into natural gas through P2G for storage. At the higher electricity price(10:00-15:00,18:00-21:00), the cost of purchasing power from the power grid is too high, and lower cost cogeneration units and gas turbines can be used to cooperate with renewable energy to provide the electrical load; the demand side response reduces or shifts the load according to the time-of-use electricity price. At the peak of the electricity price, the park can sell unused electricity to earn additional income, which is also a measure to reduce the operating costs in the park.
In scheme 1, there is no electricity conversion and gas storage equipment, and all the gas load is satisfied by the gas purchase from the gas network all day. Meanwhile, CHP and GT also have gas consumption behaviours, resulting in excessive gas purchase costs in the park.

In scheme 4, the electricity-to-gas and gas-storage equipment enables two-way conversion between electricity and gas, and the energy purchase and energy use methods become flexible. At the lower electricity price, P2G converts electricity into natural gas (P2G converts 3039.053 kWh power into 200.517 m³ gas), which can supply gas load and store it. At the higher power price, P2G stop working, the park's units will be satisfied by the gas network and the gas storage equipment within the time period of 7:00-22:00; when the capacity of the gas storage reaches the limit, it will be used as a backup and will no longer participate in system regulation.

In scheme 1, the heat load of the park only depends on the consumption of natural gas and electric energy by CHP and EB;

In scheme 4, the heat storage broke the principle of "determining electricity with heat", so the heat load can participate in the park dispatch. At the lower electricity price (00:00-07:00, 23:00-24:00), thermal load provided by the EB. At the higher electricity price, the cost of electricity to heat is rising, and the EB stops operation and changes to auxiliary function. Its output depends on the electricity price, load condition and energy storage. Meanwhile, CHP unit can use low-cost gas to heat, and coordinate the output with heat storage equipment to meet the heat load.

3.2. Dispatch cost analysis

The economic dispatching period of the park is 24 hours, the unit dispatching time \( \Delta t=1 \) h; Table 2 shows the electricity purchase cost, gas purchase cost, electricity sales revenue and total expenses in the park under the four schemes.
Table 2. Park operating costs.

| Scheme | Cost of electricity (yuan) | Cost of gas (yuan) | Cost of units start or stop (yuan) | Cost of demand response (yuan) | Sale of electricity (yuan) | Total expenses (yuan) |
|--------|---------------------------|--------------------|-----------------------------------|------------------------------|---------------------------|---------------------|
| 1      | 1174.8                    | 3376.1             | 5.8                               | 0                            | 9.7                       | 4547                |
| 2      | 1189.8                    | 3267.9             | 18.6                              | 0                            | 33.2                      | 4443.1              |
| 3      | 2227.8                    | 2201.8             | 18.6                              | 0                            | 33.2                      | 4415                |
| 4      | 1918.7                    | 2170               | 139                               | 35                           | 63.9                      | 4198.8              |

In Scheme 1, there is no energy storage unit, and the energy can’t be stored, less power can be sold and the total cost is higher;

Scheme 2 adds the heat storage equipment. The heat storage equipment promotes the output of EB at low electricity prices. After converting power into heat and providing the heat load, it can also increase electricity purchase and convert it into thermal for storage; At the peak of electricity price, the heat load can be supplied by the heat storage, reduce the electricity consumption of the EB, increase the electricity sold to the outside and the additional income.

Scheme 3 adds the P2G and gas storage. The combination of heat storage and gas storage units improve the flexibility of park’s energy scheduling. At the lower electricity price, the cost of gas purchase from the gas network is higher than power to gas; The P2G used to convert low-cost electrical energy into gas for storage, reducing the cost of natural gas.

Scheme 4 adds load-side demand response, which flexibly dispatches loads based on time-of-use electricity prices; At the higher electricity prices, the shiftable load is transferred out, reducing the power load and the cost of electricity, and increasing the revenue from additional electricity sales. At the lower price, it is transferred to the electric load, and it can be flexibly shifted according to the load during the normal period;

4. Conclusion
This paper establishes a multi-energy complementary integrated energy system for the park’s economic dispatch model. It comprehensively considers the power and gas purchase costs of the energy network and the start or stop costs of various unit in the park, aim to absorb renewable energy and decrease park dispatch costs, following conclusions are drawn through the analysis of case examples:

(1) The electric to gas and electric to heat units realize the mutual conversion of energy and realize the mutual complementation of multiple energy in the park. At the same time, when the renewable energy output is large, the natural gas and thermal energy converted from electric energy are respectively used to effectively reduce the phenomenon of wind and light abandonment and improve the new energy consumption capacity;

(2) The introduction of heat storage equipment breaks the traditional way of "fixed electricity by heat", converts the electric energy or surplus electric energy in the valley period into heat energy storage, releases heat in the peak period of electricity price, and flexibly participates in the electric heat dispatching; the introduction of gas storage equipment can convert the electric energy or surplus electric energy in the valley period into natural gas storage through p2G equipment. The introduction of energy storage equipment can effectively strengthen the consumption of renewable energy in the park, improve the permeability of renewable energy, and effectively reduce the cost of gas purchase and heating in the park.

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