Planning and Optimal Scheduling Method of Regional Integrated Energy System Based on Gray Wolf Optimizer Algorithm

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Abstract. For the regional integrated energy system (RIES) with multi-energy complementary, it is key to plan and optimize scheduling, which can improve energy efficiency. This paper focuses on the planning and scheduling of the RIES with self-provided waste incineration power plant. A bi-level mathematical model of the RIES with electricity, heat, cooling and gas interconnection is built. The upper level takes the minimum annual comprehensive cost as the optimization objective to find the optimal configuration. Based on the configuration scheme provided by the upper level, the optimized scheduling scheme under the economic and environmental indicators is developed by using some constrains, such as the supply and demand balance and equipment output operation. At the same time, the policy subsidy of self-provided waste incineration power plant and the transaction cost of pollutant emission are considered in the optimal scheduling. Then the gray wolf optimizer algorithm is proposed to solve the bi-level optimization problem. The effectiveness and superiority of the planning and optimal scheduling model proposed are demonstrated by analyses in typical scene.

1. Introduction
The regional integrated energy system (RIES) can organically coordinate energy production, transmission, distribution, conversion, storage, consumption and other links, which is of great significance for building energy Internet, improving energy utilization and promoting renewable energy development. At present, the research on regional integrated energy system mainly focuses on system planning, optimal scheduling and other aspects [1-7]. Many researchers try to use different optimization algorithms to solve the problem, including the algorithm based on interval linear programming model, differential evolution independent component analysis (DE-ICA) algorithm, particle swarm optimization (PSO) algorithm, non dominated sorting genetic algorithm (NSGA-II), etc., but there are still some problems of timeliness and accuracy in solving the problem of nonlinear mixed integer programming. The existing comprehensive energy system planning equipment is mainly CCHP, wind energy, photovoltaic, refrigeration, heating and energy storage equipment, and there isn’t refuse incineration power plant. At present, waste classification is being implemented in China. Therefore, it is necessary to build the self-provided waste incineration power plant, which can make use of waste energy resources and meet the sustainable development of energy. In this paper, the self-provided waste incineration power plant is included in the park planning, and the planning and optimal scheduling of RIES based on gray wolf optimizer algorithm are studied.
2. Bi-level Optimal Allocation Planning Model for RIES

2.1 Basic Structure of RIES

In this paper, the RIES covers the main energy types, such as electric energy, thermal energy, natural gas, and all kinds of energy conversion and storage equipment. The specific framework of the multi-energy complementary micro energy network is shown in Figure 1. Its input is connected to the power grid, natural gas and regional heat-supplying net, and its output provides multi energy services for the user side, including power supply, hot, cold and gas. There are distributed renewable energy such as wind energy, photovoltaic power generation and self-provided waste incineration power plant. The energy conversion equipment, including gas boiler, electric boiler and electric refrigerator are adjustable units.

![Figure 1. Frame of multi-energy complementary micro-energy network.](image)

2.2 Planning Optimization Model of RIES

2.2.1 The objective function and constraints of the upper level.

The objective function of planning model of the upper level is to minimize the annual comprehensive cost, and the decision variables are the installation type and quantity of energy equipment. The annual comprehensive cost is the sum of the equivalent annual investment cost $C_{\text{Inv}}^{\text{Equ}}$ and the lower feedback daily cost $C_{\text{undr}}$.

$$\min C = C_{\text{Inv}}^{\text{Equ}} + Y C_{\text{undr}}$$  \hspace{1cm} (1)

$$C_{\text{Inv}}^{\text{Equ}} = \sum_{i,k} O_{i,k} \varphi_i^{\text{Equ}} C_{i}^{\text{Inv}}$$  \hspace{1cm} (2)

Where $O_{i,k}$ is a 0-1 variable, indicating whether the $k$-th class $i$ energy equipment is configured. When the equipment is configured, $O_{i,k} = 1$, otherwise $O_{i,k} = 0$. $C_{i}^{\text{Inv}}$ is the initial investment cost of class $i$ energy conversion and storage equipment, $\varphi_i^{\text{Equ}}$ is the capital recovery rate of class $i$ energy conversion and storage equipment equivalent cycle, which is described as follows:

$$\varphi_i^{\text{Equ}} = \frac{\lambda(1+\lambda)^{Y_i}}{(1+\lambda)^{Y_i}-1}$$  \hspace{1cm} (3)

Where $\lambda$ is the discount rate (6.0%), $Y_i$ is the service life of class $i$ equipment.

The constraints of planning model include the maximum load constraints of electric, heating, cooling conditioning and the number of equipment installed.

$$\sum_{j} Q_{\text{max},j}^E \geq I_{\text{max}}^E$$  \hspace{1cm} (4)

$$\sum_{j} Q_{\text{max},j}^H \geq I_{\text{max}}^H$$  \hspace{1cm} (5)
\sum_{j} Q_{\text{max},j}^C \geq I_{\text{max}}^C \quad (6)

Where \( Q_{\text{max},j}^C \) is the maximum power supply of type \( j \) power supply equipment, \( I_{\text{max}}^C \) is the electrical load designed in the RIES. Similarly, equation (5) and equation (6) are heating and colding maximum load constraints.

2.2.2 The objective functions and constraints of lower level. For the daily scheduling optimization of the lower level, the economic and environment indicators of RIES are considered. For the economic indicator, there are the maintenance cost of various energy generation, transfer storage equipment and the purchase cost of external network.

\[ C_{\text{Op}} = C_{\text{OM}} + C_{\text{buy}} \quad (7) \]

\[ C_{\text{OM}} = \sum_{i} \sum_{k} \sum_{t} q_{i,k,t}^{\text{EC}} P_{i,k,t}^{\text{out}} + \sum_{i} \sum_{k} \sum_{t} q_{i,k,t}^{\text{ES}} P_{i,k,t}^{\text{ES}} + \sum_{i} \sum_{k} \sum_{t} q_{i,k,t}^{\text{RES}} P_{i,k,t}^{\text{RES}} \quad (8) \]

\[ C_{\text{buy}} = \sum_{t} \left( c_{t}^{\text{buy}} \cdot P_{t}^{\text{buy}} \right) \Delta t \quad (9) \]

Where \( P_{i,k,t}^{\text{out}} \) is the output power of the \( k \)-th class \( i \) conversion equipment in \( t \) period. \( P_{i,k,t}^{\text{ES}} \) is the charging and discharging power of the energy storage equipment in \( t \) period. \( P_{i,k,t}^{\text{RES}} \) is the output power of the renewable energy equipment in \( t \) period. \( q_{i,k,t}^{\text{EC}}, q_{i,k,t}^{\text{ES}} \) and \( q_{i,k,t}^{\text{RES}} \) are the operation and maintenance costs of class \( i \) energy conversion equipment, class \( j \) energy storage equipment and class \( l \) renewable energy equipment respectively. \( P_{t}^{\text{buy}} \) and \( c_{t}^{\text{buy}} \) are the purchase energy and purchase price of RIES and power grid in \( t \) period.

For environment indicator, the environmental protection cost of RIES is the difference between the transaction cost of pollutant emission and the subsidy of waste incineration policy. With reference to quota based trading market, it is defined to charge trading cost of pollutant emission \( C_{\text{pol}} \) according to pollutant emission exceeding quota. Define the relationship between waste incineration policy subsidy \( C_{\text{sub}} \) and operating power of self-provided waste incineration power plant. They are shown in equation (10) and equation (11) respectively.

\[ C_{\text{pol}} = \sum_{t} \left[ w(t) \cdot (E_{i,t} - E_{i,t,\text{int}}) \right] \quad (10) \]

\[ C_{\text{sub}} = \mu v P_{\text{was},t} \Delta t \quad (11) \]

The constraints of the lower level scheduling model include the energy power balance and equipment operation of electricity, heat, cold and gas, etc.

\[ \sum_{k} P_{i,k,t}^{\text{ele}} \geq P_{e,t} \quad (12) \]

\[ \sum_{k} P_{i,k,t}^{\text{heat}} \geq P_{h,t} \quad (13) \]

\[ \sum_{k} P_{i,k,t}^{\text{cool}} \geq P_{c,t} \quad (14) \]

\[ \sum_{k} P_{i,k,t}^{\text{gas}} \geq P_{g,t} \quad (15) \]

\[ P_{t}^{\text{min}} \leq P_{t,i} \leq P_{t,i}^{\text{max}} \quad (16) \]

Where \( P_{i,k,t}^{\text{ele}} \) is the output power of the \( k \)-th type \( i \) power generation and storage equipment (including the power purchased from the power grid), \( P_{i,k,t}^{\text{heat}}, P_{i,k,t}^{\text{cool}}, P_{i,k,t}^{\text{gas}} \) are the output power of heat generation and storage equipment, cold generation and storage equipment, and gas generation.
equipment. $P_{e,t}, P_{h,t}, P_{c,t}, P_{g,t}$ are the demand load of the RIES at time $t$, $P_{t}^{i,max}$ and $P_{t}^{i,min}$ are the minimum power and the maximum power of any type $i$ equipment in normal operation.

3. Model solution

3.1 Gray Wolf Optimizer Algorithm

In order to improve the convergence and reduce the convergence time, the gray wolf optimizer algorithm is used to solve the upper level programming model. Grey wolf optimizer algorithm (GWO) is a new group intelligent optimization algorithm which simulates the hierarchy and predatory behavior of grey wolf population. The grey wolf group follows the hierarchical social system, which is divided into $\alpha, \beta, \sigma$ and $\omega$ levels, which are defined $\alpha$ as the historical optimal solution of the group, $\beta$ is the suboptimal solution, $\sigma$ is the third optimal solution, and others are $\omega$. In the search space, the gray wolf group is updated when it moves:

$$X_{p}^{d}(t+1) = X_{p}^{d}(t) - A_{i}^{d} |C_{i}^{d} X_{i}^{d}(t) - X_{i}^{d}(t)|$$

Where $t$ is the current number of iterations, $X_{p}^{d}(t)$ is the position of prey in d-dimensional space, $A_{i}^{d} |C_{i}^{d} X_{i}^{d}(t) - X_{i}^{d}(t)|$ is the step length of wolves' encirclement on prey. $A$ is the convergence coefficient, used to balance global search and local search. $C$ represents the influence of nature.

The grey wolf population updates their positions according to the positions of the first three optimal solutions, and the updating equation is as follows:

$$X_{i}^{d}(t+1) = X_{\alpha}^{d}(t+1) + \frac{X_{\beta}^{d}(t+1) + X_{\sigma}^{d}(t+1)}{3}$$

3.2 Model Solution

Based on GWO algorithm, upper-level planning optimization is carried out, each individual is a planning scheme, the dimension of each particle in the algorithm represents the specific configuration of equipment, the position of each particle represents the number of equipment configurations, and the objective function is taken as the fitness value of the algorithm. After obtaining the configuration scheme, the planning result is sent to the lower layer, and the optimal daily scheduling scheme of the lower layer is obtained based on cplex solver. The decision variable is the scheduling situation of energy equipment, and the operation cost is transferred to the upper layer to calculate the objective function value of the upper layer. The input and output of the upper and lower layers are iterated repeatedly, and the optimization target value gradually converges to the optimal value.

4. Result and discussion

4.1 Simulation Analysis

The case park is an intelligent community energy internet demonstration project in Beijing. The demand of power and gas load can be estimated by building area and historical data. The cooling load and heat load are affected by temperature difference, solar radiation, indoor load and infiltration load inside and outside the room. The energy demand of the park is provided by the comprehensive energy microgrid, and the power load, heat load, cooling load and gas load are independent of each other. Distributed renewable energy includes wind energy, photovoltaic power generation and self-provided waste incineration power plant. The output power of photovoltaic power generation is mainly affected by solar radiation intensity and ambient temperature, which can be estimated by analyzing the historical solar radiation intensity and ambient temperature in this area. Wind power generation is also affected by the environment and other factors. The typical daily wind power output data is selected as the input power.

The peak hours of electricity consumption in the park are 12:00 - 14:00 and 19:00 - 22:00, and the peak electricity price is 1.21 yuan/(kWh). The normal period is 08:00 - 11:00 and 15:00 - 18:00, and
the price is 0.89 yuan/(kWh). The trough period is 23:00 - 07:00, the trough electricity price is 0.48 yuan/(kWh), and the natural gas and thermal prices are 0.27 yuan/(kWh) and 0.30 yuan/(kWh) respectively after conversion into a unified unit.

4.2 Simulation Results
GWO algorithm is used to optimize the upper-level planning, and particle swarm optimization (PSO) algorithm is also used for comparison. The convergence curves of the two algorithms are shown in Figure 2. It can be seen that in terms of convergence speed of PSO algorithm tends to be stable after 30 iterations, and GWO algorithm tends to be stable after 10 iterations. The convergence performance of the GWO is better than of the PSO. It shows that the GWO algorithm can improve the quality of the solution and balance global search and local search.

![Figure 2. Convergence performance of GWO and PSO.](image)

![Figure 3. Renewable energy and hourly load.](image)

By inputting the planning results of upper level into the lower level, the daily scheduling optimization results of lower level can be obtained. They are shown in Figure 4.

![Figure 4. Daily dispatching plan for four loads.](image)

The power dispatch plan of RIES is shown in Figure 4 (a). Due to the time-of-use price, the less power is purchased from the power grid at the peak of the electricity price, and more power is

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purchased from the power grid at the lower price. When the environment indicators is considered, the output of gas turbine decreases in the scheduling scheme. Especially when the electricity price is relatively low, such as 15:00-18:00, the gas turbine load is reduced, and the external power purchase is increased, which plays a complementary role.

The heat supply dispatch plan of RIES is shown in Figure 4(b). The high load operation time of electric boiler is the low price period (0:00-11:00), the heat-supplying of RIES is completed by the electric boiler, and the two peaks of external purchasing heat occur in the time when the electricity price is higher.

Figure 4(c) is a cooling dispatch plan. In the scheduling scheme, the absorption refrigeratory is not selected because the energy conversion efficiency of the electric refrigeratory is 3.5, which is much higher than 0.7 of the absorption refrigeratory. The gas supply dispatch plan is shown in the Figure 4(d). The system purchases gas from the gas network, which not only meets the gas load demand of the park, but also the demand of gas turbine and gas boiler.

As can be seen in Figure 4(a), the self-provided waste incineration power plant play an important role in the scheduling scheme of RIES. Due to the high power generation efficiency and low maintenance cost, the waste incineration power plant is always preferred in power dispatching. And its daily operation cost is reduced effectively because of the policy subsidy. Therefore, it is very efficient to plan the self-provided waste incineration power plant in the RIES. It improves the environmental and social benefits of RIES.

5. Conclusion

In this paper, the planning and scheduling of the RIES with self-provided waste incineration power plant is studied. A bi-level mathematical model of the RIES with electricity, heat, cooling and gas is built. The economic and environmental indicators are adopted as optimization objectives of bi-level model of RIES, and optimized by using the GWO algorithm. The effectiveness and superiority of the planning and optimal scheduling model proposed are demonstrated by analyses in typical scene. It shows that the solving process of the bi-level planning and scheduling of RIES is improved based on the GWO algorithm. And the self-provided waste incineration power plant is planned in the RIES, which is scheduled preferentially and the resource and energy are saved.

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