Multi-objective operation optimization of regional integrated energy system based on NSGA-II algorithm

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Abstract. With the deepening of China's energy market reform and the promotion of integrated energy services, the regional integrated energy system becomes an important development direction of energy supply system. In order to maximize the economic efficiency and reduce the air pollutant emission of the regional integrated energy system, the distributed power generation module and the cooling-heat-power (CCHP) triple-supply module are formed into a model, and the power balance, equipment capacity and environmental factors of the system are constrained with the objective function of minimizing the daily operation cost of the system as well as minimizing the air pollutant emission. Based on the mathematical system framework model and the optimal operation control strategy, the NSGA-II algorithm is used to solve the multi-objective programming model to obtain the Pareto solution set, and the hourly output of the optimal operation of the system equipment with both economic and environmental benefits is obtained. The results show that the daily operating costs and pollutant emissions of the district energy system are significantly reduced compared with those without optimization, which effectively solves the problems of low operating efficiency and serious environmental pollution of the district energy system and achieves the optimal operation with both economic and environmental benefits.

1 Introduction

As the world's largest energy producer and consumer, China has been facing the problem of energy supply shortage and how to save energy and reduce emissions efficiently [1-2]. In the transformation of energy structure, the combined cooling-heat-power (CCHP) system based on the principle of energy gradient utilization can meet the demand of cooling, electricity and heat at the same time. Its efficient energy utilization provides great opportunities to save energy and reduce air pollutant emissions. The performance of CCHP system is closely related to a reasonable and feasible optimized operation strategy, and the lack of system configuration and operation strategy will result in low system operation efficiency, poor economy and serious environmental pollution.

2 Structure and model of regional integrated energy system

Regional integrated energy system is a new type of energy supply system with high integration and complexity. This energy system includes electric power supply system, and also involves various energy supply systems such as cooling and heating system and natural gas system.

2.1. Framework of Multi-energy Complementary Cooling-Heat-Electricity Combined Supply System

The regional integrated energy system considered in this paper has a distributed power generation system as its input [3]. The power supply system passes through different energy conversion equipment to output cooling demand, heating demand and power supply demand.

Figure 1. Simulation architecture of multi-energy complementary cooling-heating-electricity combined supply system.

As shown in the Figure1: the core energy supply equipment is an internal combustion generator set, which generates electricity by inputting natural gas energy to

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meet the electrical load demand. The jacket water waste heat and flue gas waste heat generated by its operation are recovered and reused by the waste heat recovery device. One part is directly used to supply heat load, and the other part is used to drive the lithium bromide absorption chiller to produce cold energy. In addition, gas-fired boilers and electric refrigerators function as peak-shaving equipment, operating when the heat or cold supply is insufficient to ensure the balance of energy supply and demand.

This energy supply framework considers the temporal and spatial characteristics of different energy sources, coordinates the safe operation of various equipment, and guarantees the reliable supply of multiple loads, so as to improve the overall energy utilization rate of the system and the consumption rate of renewable energy.

2.2 Energy supply equipment

2.2.1 Photovoltaic power generation

Photovoltaic power generation: Photovoltaic power generation (PV) is the use of solar energy to convert light energy into electrical energy by using semiconductor materials made of semiconductor materials on the surface of its equipment [4]. The actual power generation of solar panels can be calculated by the following formula:

$$P_{PV} = \eta_{pv} \cdot H_s \cdot S_p \cdot N_{pv} / H_{STC} \quad (1)$$

where, H_s is the actual light radiation density, S_p is the area of a single PV panel, N_{pv} is the total number of PV panels, η_{pv} is the PV power conversion efficiency factor, H_{STC} is the light radiation density under standard test conditions.

2.2.2 Gas turbine power generation

The gas turbine (GT), as the prime mover in the combined cooling-heating-electricity system, burns natural gas to produce high-temperature gas for expansion and work, thereby driving the impeller to rotate at a high speed, and the impeller drives the generator to generate electricity. Its electric power and the waste heat output power can be calculated by the following formulas:

$$P_{GT} = \eta_{GT}^e \cdot V_g \cdot q_g \quad (2)$$

$$Q_{GT} = \eta_{GT}^h \cdot V_g \cdot q_g \quad (3)$$

where, η_{GT}^e is the power generation efficiency of gas turbine, V_g is the natural gas consumption rate, m^3/s , and

q_g is the natural gas calorific value, J/m^3 , η_{GT}^h is the heat production efficiency of the gas turbine.

2.2.3 Internal combustion engine power generation

Gas internal combustion engine (GE) refers to a natural gas internal combustion engine generator set. It generates high-temperature and high-pressure gas through the combustion of natural gas and air in the cylinder. Its expansion work drives the piston to move, thereby driving the crank connecting rod and other devices to produce mechanical energy.

$$Q_{GE} = \eta_{GE}^h \cdot V_g \cdot q_g \quad (4)$$

where η_{GE}^h is the heating efficiency of the gas internal combustion engine.

2.2.4 Gas boiler equipment

Gas-fired boilers (GB) mainly use gas-fired hot water boilers in the regional integrated energy, and produce hot water for end users by burning natural gas. The mathematical model of the gas turbine output can be described as follows:

$$Q_{GB} = \eta_{GB} \cdot V_g \cdot q_g \quad (5)$$

where, η_{GB} is the operating efficiency of the gas boiler.

2.2.5 Photothermal boiler

The solar thermal boiler (SH) uses solar collector panels to absorb heat from sunlight, then the heat transfer mass is heated by the solar collector panels, and then circulated through the pipes to the heat exchanger for heat transfer to heat the cold water.

$$Q_{SH} = \eta_{SH} \cdot H_s \cdot S_{sp} \cdot \eta_{ch} \cdot N_{ch} \quad (6)$$

where η_{SH} is the thermal conversion efficiency of the solar hot water boiler; S_{sp} is the area of a single solar collector, in m^2 ; η_{ch} is the efficiency of the collector; N_{ch} is the total number of solar collectors.

2.2.6 Electric chiller

Electric chiller (EC) is driven by the motor running the piston of the compressor for compression, so that the refrigerant material inside the compressor is liquefied under pressure, releasing heat to the outside world, and the liquefied refrigerant material can evaporate and absorb heat, thus realizing the transfer of heat.

$$Q_{EC} = COP_{EC} \cdot P_{EC} \quad (7)$$

where, Q_{EC} is the unit time output cold energy of electric refrigeration machine, unit kW; P_{EC} is the unit time input electric energy of electric refrigeration machine, unit kW; COP_{EC} is the refrigeration coefficient of electric refrigeration machine.

2.2.7 Absorption chiller

Absorption chiller (AC), which uses thermal energy as an input energy source to cool a refrigerant by the process of evaporative heat absorption and condensing heat release in a series of devices.

$$\begin{cases} COP_{AC} = f(r) = \sum_{i=0}^3 \beta_i(r)^{(3-i)} \\ r = \frac{p}{P_{max}} \\ Q_{AC}^{out} = COP_{AC} Q_{AC}^{in} \end{cases} \quad (8)$$

where COP_{AC} is the coefficient of absorption chillers machine.

3 Economic and environmental friendly operation design

3.1. Objective function

The hybrid cooling-thermal-electric energy system model proposed in this paper contains the objective functions of both economic and environmental protection benefits, resulting in the minimum daily operating costs of the system and the minimum air pollutant emissions.

3.1.1 Economic benefits

The daily operating economic cost cost of a hybrid cooling-heat-electric energy system consists of the following two main aspects: fuel cost, and power cost of grid interaction:

$$\min pri_{eco} = \min(pri_{fuel} + pri_{power}) \quad (9)$$

$$\begin{aligned} pri_{fuel} = & \sum_{t=1}^{24} \sum_{i=1}^{n_{CHP}} c_{Gas}^t \times f_{CHPi}(P_i^t) \\ & + \sum_{t=1}^{24} \sum_{i=1}^{n_{GBi}} c_{Gas}^t \times F_{GBi}^t \end{aligned} \quad (10)$$

In this case, the fuel cost of micro gas turbine and gas boiler is calculated as a function. Where, f_{CHPi} is the consumption characteristic curve function of micro gas

turbine, P_i^t is the electric power output of the i-th micro gas turbine in kW; c_{Gas}^t is the hourly gas price in yuan/kWh converted from the natural gas calorific value; F_{GBi}^t is the consumption of the i-th gas boiler in kW in time period t . The power interaction cost function between the system and the grid is calculated as follows:

$$pri_{power} = \sum_{i=1}^{24} c_{power}^t \times P_{power}^t \quad (11)$$

where, c_{power}^t is the hourly electricity price; P_{power}^t is the hourly electricity exchange value between the interconnection system and the external grid.

3.1.2 Environmental protection benefits

The environmental benefits target considers the total emissions of carbons, nitrogen and sulfides, and the total pollutant emission levels are expressed as follows:

$$pri_{environment} = \min(f(G_C) + f(G_S) + f(G_N)) \quad (12)$$

where $f(G_C)$, $f(G_N)$, $f(G_S)$ are the daily carbon emission value, daily sulfide emission value and daily nitrogen emission value of the park, respectively, as follows:

$$f(G_C) = \sum_{t=1}^{24} \sum_{i=1}^n (E_i^{CO} + T_i^{CO} + B_i^{CO}) \times \Delta t \quad (13)$$

where E_i^{CO} , T_i^{CO} , B_i^{CO} are the CO_x emissions from the park's purchase of electricity from the public grid, micro gas turbines and gas boilers, respectively, in kg/h. Nitride and sulfide represented by SO and NO are similar to CO carbide.

3.2 Constraints

3.2.1 The electric power balance

The constraint condition of the day-ahead economic optimization dispatch model of the cold-heat-electric hybrid energy system is mainly the power balance constraint.

$$\sum_{i=1}^{n_{GT}} P_i^t + \sum_{i=1}^{n_{PV}} P_{PV}^t + P_{power}^t = P_{Load}^t \quad (14)$$

where P_{power}^t is the time-to-time power exchange value between the interconnection system and the external grid; P_{Load}^t is the load value; P_{PV}^t is the power of the distributed generation equipment; P_i^t is the power generated by the i-th micro-gas turbine.

3.2.2 The thermal power constraint

For the heat load, the hot water from the waste heat boiler and gas boiler is exchanged for heat through the heater and the surrounding space when the space heat load is satisfied. The total thermal power balance constraint is calculated as follows:

$$\sum_{i=1}^{n_{GT}} H_i^t + \sum_{i=1}^{n_{GB}} H_{GB}^t \geq H_{Water}^t \quad (15)$$

where H_i^t is the heat value recovered by the i-th micro gas turbine through the waste heat boiler; H_{GB}^t is the heat production value of the ith gas boiler; H_{Water}^t is the time-by-time space heat load.

3.2.3 The cooling power constraint

For the cold load, the low-temperature chilled water prepared by these two devices is exchanged through fan

coils and surrounding space for heat exchange when the space cold load is satisfied.

$$\sum_{i=1}^{n_{GT}} C_i^t + \sum_{i=1}^{m_{GB}} C_{EC}^t + EER_{cond} \times P_{cond}^t \geq C_{Freeze}^t \quad (16)$$

where, C_i^t is the cooling capacity made by the i-th micro gas turbine through the absorption chillers; C_{EC}^t is the value of chilled water produced by the electric chiller; EER_{cond} is the chillers energy efficiency ratio; C_{Freeze}^t is the time-by-time space cooling load in the hybrid energy system.

3.3 NSGA-II algorithm

The optimization of the operation of the energy system in this region requires consideration of both economic and environmental objectives, this paper proposes to solve the system operation optimization problem using NSGA-II algorithm [5-6].

Figure 2. NSGA-II algorithm flow chart.

4 Case Simulation

4.1. Parameter setting

The annual cooling, heating and electricity load demand and solar radiation density of this park are represented using a typical day, as shown in Figure 3.

Figure 3. Load and solar radiation density variation curve of a typical day in summer

The peak, valley and flat prices of energy are shown in Table 3-1, where the prices of electricity purchased from the grid vary at peak, flat and valley times, while the price of natural gas is always constant. Table 3-2 shows the economic and technical parameters of the main equipment in the system, including its efficiency, cost, lifetime and load range. Table 3-3 shows the main equipment emission indicators and has converted the emissions into g/kW*h units, which represent the pollution emissions per kW*h of electricity, heat, and cooling produced.

Table 1. Price of each energy source.

Energy	Price (yuan/kW)		
	Peak time	Ordinary time	Valley time
Electricity	1.0181	0.6370	0.3496
Gas	0.312	0.312	0.312

Table 2. Main equipment emission index.

Emission factors	GE	GT	GB	Public network	AC
CO _x	551	728	255	920	173
NO _x	0.16	0.19	0.54	2.295	0.06
SO _x	0.003	0.004	0.77	3.58	0.0008

4.2. Optimized control strategy

The simulation process of optimal control of a regional integrated [7] energy system is as follows:

Step 1: Basic data input. Cooling, heating and electricity load data, distributed PV output data and energy price (electricity price, natural gas price) data.

Step 2: Simulation of multi-objective optimal control based on NSGA-II algorithm. Based on the multi-energy complementary cooling-heating-electricity combined supply system established in this paper, the NSGA-II algorithm is used to perform multi-objective optimal

control operation simulation with the objective function of minimizing daily operating costs and environmental emissions.

Step 3: Result analysis. The objective function values output from the simulation and the output of each unit in the system are analyzed to realize the optimization and energy saving of the system in both economic and environmental aspects.

Figure 4. Flow chart of optimal control simulation

4.3. Optimization results

The NSGA-II algorithm is applied to the multi-objective operation optimization of integrated energy system.

Figure 5. Adaptation curve of NSGA-II algorithm

The initial population size is set to 2000, each individual is the output value of cooling, heating and electricity of energy supply equipment, the crossover rate is 0.8, and the variation probability is 0.04. The maximum number of iterations is set to 300, the relative change criterion between two generations of population

individuals in the Pareto optimal solution set is set to e-1, and if the difference between two generations of individuals is less than the criterion, the Pareto optimal solution set boundary is shown in Figure 5.

From the obtained Pareto solution, a Pareto solution that is economical and environmentally friendly is selected. The total pollutant emission value is 418959.6kg/day, and the operating cost is 25788.5 yuan/day. The optimal system configuration scheme obtained is shown in Table 3, the devices that are not selected are not displayed in the table.

Table 3. Main equipment emission index.

Equipment	PV (MW)	GE (Desk)	GB (MW)	EC (MW)	AC (MW)
Capacity	7.2	5	12.5	10.3	19.5

From the simulation results, we can see that the system is always in the balance of supply and demand for electrical, thermal and cooling energy. 1:00-8:00, the system mainly purchases electricity from the grid at the lowest price; 9:00-24:00 is the time when there are more solar resources, and the electricity is mainly provided by the internal combustion engine and photovoltaic power generation. At 12:00, 14:00 and 15:00, the system also sells excess electricity to the grid.

Figure 6. Electricity supply and demand diagram of a regional integrated energy system on a typical day

Figure 7. Thermal energy supply and demand diagram of an integrated district energy system for a typical day

9:00-17:00 is the peak time of thermal load and the time when solar radiation is strongest, the solar thermal boiler produces heat to relieve the system's heating pressure and provides cold energy to customers through absorption cooling. 1:00-8:00 hours, cold energy is mainly generated through electric chillers; 9:00-24:00

hours, the waste heat from the internal combustion engine is supplied by absorption chillers. Figure 8 shows the emission of pollutants from each energy supply equipment in the case of economy and environmental protection.

Figure 8. Cold energy supply and demand diagram for a typical day of an integrated regional energy system

Figure 9. Pollutant emissions from various types of energy supply equipment

Table 4. Comparison system economy and environment.

Control Strategy	Daily running cost (yuan/day)	Pollutant emissions (kg/day)
Before optimization	32658.2	568724.1
After optimization	25788.5	418959.6

The pre-optimized system, where the electric load is all purchased from the public network, the hot water load is met by a gas boiler, and the cooling load is met by an electric chiller, has a daily operating cost of 32,658.2 yuan, as well as daily pollutant emissions of 568,724.1 kg under this energy supply scenario. After adopting the economic and environmental multi-objective optimization strategy, the daily operating cost of the system is reduced by 21.04%, and the pollutant emission is reduced by 149,764.5 kg per day, which shows that by adjusting the operation mode and output of each energy supply equipment in the cold-heat-electric hybrid energy system, not only the daily operating cost of the system can be significantly reduced, but also the environmental pollutant emission is significantly reduced, and the cold-heat-electric hybrid energy system is realized.

5 Conclusion

This paper focuses on the multi-objective optimal operation of the cooling-thermal-electricity integrated energy system based on NSGA-II algorithm. The system model mainly includes distributed power generation module and cooling-heating-electricity triple-supply module, which can realize the graded high-efficiency utilization of energy as well as the reduction of environmental pollutants. Therefore, based on the analysis of the energy supply structure and operation strategy of the regional integrated energy system, this paper establishes the planning and operation optimization model of the regional integrated energy system, and uses NSGA-II algorithm for multi-objective planning and operation optimization, with typical NSGA-II algorithm is used for multi-objective planning and operation optimization, and the hourly output of each equipment in operation is allocated with the objective of taking into account the economic optimum and the lowest environmental pollution emission. Based on the simulation results of this paper, the daily operating cost is reduced by 21.04% and the pollutant emission is reduced by 149,764.5 kg per day, which effectively solves the problems of low operating efficiency of the district energy system, single energy supply structure and high environmental pollution emission, and achieves the operation optimization with both economic and environmental benefits.

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