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Energy Flow Function and Operational Strategy of CCHP System

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Abstract: The energy flow characteristics of Combined Cooling, Heating and Power (CCHP) system are analyzed in detail and the energy flow function is proposed for its two operational strategies: thermal load dominant mode and electrical load dominant mode. In order to improve its economic and environmental efficiency, an optimal economic and environmental dispatch model is built, which includes the fuel cost, power purchase cost and pollution emission penalty as environmental cost in its objective function and takes the energy flow function as its energy balance equality constraint. Case simulation shows that, the proposed energy flow function and model optimizes the dispatch of CCHP system, reduces the productive cost, improves the environmental efficiency and enhances the energy utilization level.

Keywords: CCHP, operational strategy, energy flow function, thermal load dominant mode, electrical load dominant mode, optimization model.

1. INTRODUCTION

CCHP system can provide cold energy, thermal energy, electrical energy and other forms of energy simultaneously to users. Owing to the advantages of energy cascade utilization and less polluting emissions, CCHP gets wide attention across the world [1]-[3]. Different operational strategies determine the economical efficiency and environmental protection property of a CCHP system: thermal load dominant mode and electrical load dominant mode [4]. The former mode preferentially meets heat load demand and the electricity shortage or surplus can be balanced by the connected main grid. On the contrary, the latter mode preferentially meets electricity load demand and the heat shortage can be provided by auxiliary boilers. As for the islanded MG where there is no dependence on the main grid, CCHPs should be in electricity-load-based mode because ac-electrical systems require a precise electricity balance at all times [5]-[8].

In order to give full play to the advantages of CCHP system energy-step-utilization and use renewable energy efficiently, PV panels is integrated into the traditional CCHP system driven by gas engines. By coordinated scheduling and optimization between solar system and CCHP system, the energy and environmental benefits could be improved greatly [9]. On the basis of CCHP system, biomass power generation, fuel cell and various energy storage device, e.g. battery, storage tank and ice storage device are taken into consideration, which increases the operational cost of the system to some extent, whereas the energy supply reliability and renewable energy usage improve a lot [10]. For different operating strategies of the system, with the annual load of cooling, heating and power as equality constraints, different objective functions [11]-[13], e.g., utilization rate of primary energy, operational cost and carbon dioxide emissions, are determined. These documents take the cumulative heat and electricity balance in a certain period into consideration, which cannot reflect the real-time balance of electricity accurately. In addition, hardly can previous studies elaborate the real-time energy flow function of the system operated under the above-mentioned two modes precisely.

Consequently, in order to tackle the issue, this paper take wind power and other renewable energy into account [14] and our research is focused on establishing the corresponding real-time energy flow function for the above two operational strategies and developing economic and environmentally friendly scheduling optimization model based on fuel cost, power purchase cost and pollution emission penalty as environmental cost.

2. CCHP SYSTEM AND ITS ENERGY FLOW

A typical CCHP system is made up of a cluster of components, e.g., gas turbine, auxiliary boilers, heat recovery steam generator(HRSG), wind Turbine and absorption chillers. As illustrated in Fig. (**1**), $F_{\mathrm{Fuel}}(\mathrm{m}^3)$, $f_{\mathrm{pgu}}(\mathrm{m}^3)$ and $f_{\mathrm{b}}(\mathrm{m}^3)$ respectively mean the natural gas consumption for the whole CCHP system, gas turbine and auxiliary boilers. For the purpose of reflecting the characteristics of the energy flow accurately, this paper use energy flow function to describe the balance state of cooling, heating and power.

where,

P_{pgu} --- the output of gas turbine, kW;

H_{pug} --- the output of HRSG, kW;

P_w --- the electricity generated by wind turbine, kW;

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P_{wc} --- the electric power provides for the system, kW;

H_a --- the heating generated by auxiliary boilers, kW;

H_{ch} --- the drive power for absorption chillers, kW;

H_c --- the generated cooling power.

Gas turbine, wind turbines and main grid operate coordinately so as to meet the electricity demand P_1(kW).

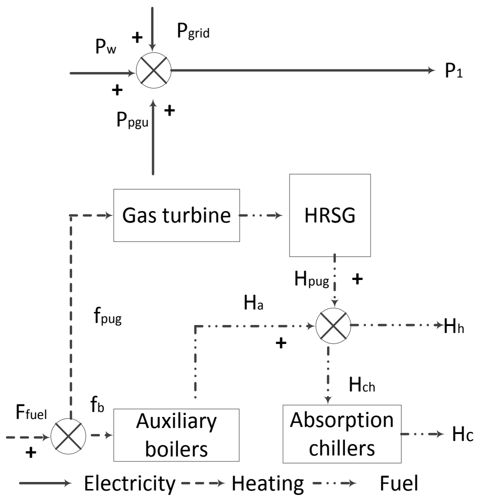

Fig. (1), Energy flow of CCHP system.

Gas turbine can simultaneously provide heating and power output, which has a certain feasible region, as shown in Fig. (**2**). The feasible region of the output of gas turbine is considered as follows:

$$x_m H_{pgu} + y_m P_{pgu} \ge z_m \quad m = 1,2,\cdots,N_{lin} \tag{1}$$

where,

N_{lin} --- the amount of linear constraints of the feasible region;

x_m�y_m�z_m --- corresponding parameters of various linear constraints.

$P_{pgu}(H_{pgu})$�$H_{pgu}(P_{pgu})$ --- function formalism of the feasible region.

Independent variables of the function change according to the operational strategies.

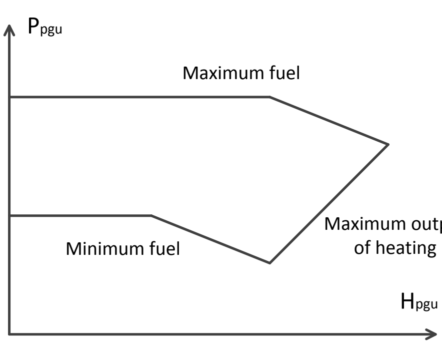

Fig. (2), Power-heat feasible operating region for PGU unit

3. THERMAL LOAD DOMINENT MODE AND ITS SCHEDULING OPTIMIZATION MODEL

3.1. Energy Flow Function of Thermal Load Dominant Mode

CCHP system operates under thermal load dominant mode preferentially satisfy the balance of thermal load. To satisfy the constraints of heating and power output and real-time balance of electric power, there should be real-time electric power interaction between the CCHP system and main grid. When the difference between electric load and total electric power generated by each generator set is greater than 0, electric power flows from main grid to the system. Otherwise, electric power flows from the system to main grid. The strategy includes 2 operational situation:

1. When the sum of thermal load and the power of absorption chillers is less than the maximum output of HRSG($H_h + H_{ch} < H_{pug}^{max}$), thermal load of the system is provided by HRSG, and auxiliary boilers are out of operation.

$$H_{pug}^{max} = H_h + H_{ch} \tag{2}$$

The output of each generator changes according to various circumstances:

1) If $P_1 < P_{pgu}^{max}(H_h + H_{ch})$, so that $P_{pgu} = P_1$ and $P_{wc} = 0$;

2) If $P_{pgu}^{max}(H_h + H_{ch}) \le P_1 < P_{pgu}^{max}(H_h + H_{ch}) + P_w$, so that $P_{pgu} = P_{pgu}^{max}(H_h + H_{ch})$ and $P_{wc} = P_1 - P_{pgu}^{max}(H_h + H_{ch})$;

3) If $P_1 \ge P_{pgu}^{max}(H_h + H_{ch}) + P_w$, so that $P_{pgu} = P_{pgu}^{max}(H_h + H_{ch})$, $P_{wc} = P_w$ and the electric load shortage is supplemented by the main grid:

$$P_{grid} = P_1 - \left[P_{pgu}^{max}(H_h + H_{ch}) + P_w\right] \tag{3}$$

2. When the sum of thermal load and the power of absorption chillers is no less than the maximum output of HRSG($H_h + H_{ch} \ge H_{pug}^{max}$), gas turbine operates at maximum thermal output and the thermal load shortage is supplemented by auxiliary boilers. This paper assumes that auxiliary boilers can meet the maximum thermal load demand.

$$H_a = H_h + H_{ch} - H_{pgu}^{max} \tag{4}$$

The output of each generator changes according to various circumstances:

1) If $P_1 < P_{pgu}^{max} \bullet H_{pgu}^{max}$, so that $P_{pgu} = P_1$ and $P_{wc} = 0$;

2) If $P_{pgu}^{max} \bullet H_{pgu}^{max} \le P_1 < P_{pgu}^{max} \bullet H_{pgu}^{max} + P_w$, so that $P_{pgu} = P_{pgu}^{max} \bullet H_{pgu}^{max}$ and $P_{wc} = P_1 - P_{pgu}^{max} \bullet H_{pgu}^{max}$;

3) If $P_1 \ge P_{pgu}^{max} \bullet H_{pgu}^{max} + P_w$, so that $P_{pgu} = P_{pgu}^{max} \bullet H_{pgu}^{max}$, $P_{wc} = P_w$ and the electric load shortage is supplemented by the main grid:

$$P_{\text{grid}} = P_1 - (P_{\text{pgu}}^{\max} \bullet H_{\text{pgu}}^{\max} + P_{\text{w}}) \tag{5}$$

3.2. Economic and Environmentally Friendly Scheduling Optimization Model of Thermal Load Dominant Mode

3.2.1. Objective Function

Objective function is composed of fuel cost($F_{\text{Fuel.C}}$), power purchase cost($F_{\text{G.C}}$) and pollution emission penalty as environmental cost($F_{\text{E.C}}$).

$$F = \min(F_{\text{Fuel.C}} + F_{\text{G.C}} + F_{\text{E.C}}) \tag{6}$$

3.2.2. Fuel cost

$$F_{\text{Fuel.C}} = \sum_{t=1}^{T} \left[C_{\text{pgu.F}}(P_{\text{pgu.i.t}}, H_{\text{pgu.i.t}}) + C_{\text{a.F}}(H_{\text{a.j.t}}) \right] \tag{7}$$

where $C_{\text{pgu.F}}(P_{\text{pgu.i.t}}, H_{\text{pgu.i.t}})$ is the total fuel cost of a certain gas turbine; $P_{\text{pgu.i.t}}$ and $H_{\text{pgu.i.t}}$ are the corresponding thermal power and electric power, respectively, �$i = 1,2,\cdots,N_{\text{pgu}}$� , $C_{\text{a.F}}(H_{\text{a.j.t}})$ is the total fuel cost of a certain auxiliary boiler; $H_{\text{pgu.i.t}}$ is the corresponding thermal power, �$j = 1,2,\cdots,N_{\text{a}}$� , T is the total dispatching times in a dispatching period.

Fuel cost of gas turbine is as followings:

$$C_{\text{pgu.F}}(P_{\text{pgu.i.t}}, H_{\text{pgu.i.t}}) = \sum_{i=1}^{N_{pgu}} (\alpha_i + \beta_i P_{pgu.i.t} + \gamma_i P_{pgu.i.t}^2 + \delta_i H_{pgu.i.t} + \varepsilon_i H_{pgu.i.t}^2 + \theta_i P_{pgu.i.t} H_{pgu.i.t}) \tag{8}$$

where,

N_{pgu} --- the number of gas turbine;

$\alpha_i, \beta_i, \gamma_i, \delta_i, \varepsilon_i, \theta_i$ --- fuel cost factors of gas turbine.

Fuel cost of auxiliary boiler is as followings:

$$C_{\text{a.F}}(H_{\text{a.j.t}}) = \sum_{j=1}^{N_{\text{a}}} (a_j + b_j H_{a.j.t} + c_j H_{a.j.t}^2) \tag{9}$$

where,

N_{a} --- the number of boilers;

a_j, b_j, c_j --- fuel cost factors of boilers.

3.2.3. Power Purchase Cost

The cogeneration system purchases power from main grid to supplement electricity shortage and sells power to main grid to improve energy efficiency. Taking peak-valley TOU pricing model into account, power purchase cost holds:

$$F_{G.C} = \sum_{t=1}^{T} [c_{sell.t} \min(\text{P}_{grid.t}\,\Delta t, 0) + c_{buy.t} \max(\text{P}_{grid.t}\,\Delta t, 0)] \tag{10}$$

where $c_{sell.t}$ and $c_{buy.t}$ ($\$/(\text{kW}\bullet\text{h})$) are the unit price of selling power and purchasing power respectively, $F_{G.C}$ means purchasing power ($F_{G.C} > 0$) or selling power ($F_{G.C} < 0$) to main grid.

3.2.4. Environmental Cost

Environmental cost is mainly the expense of processing emissions:

$$F_{E.C} = c_c \sum_{t=1}^{T} (\mu_e \max\left[(\sum_{i=1}^{N_{pgu}} P_{pgu.i.t} + \sum_{k=1}^{N_w} P_{w.k.t} + P_{l.t})\Delta_t, 0) \right] + \mu_f \left[\sum_{i=1}^{N_{pgu}} (P_{pgu.i.t} + H_{pgu.i.t}) + \sum_{j=1}^{N_a} H_{a.j.t} \right] \Delta_t) \tag{11}$$

where,

μ_e , μ_f are emission factors of polluting gases, g/(kW•h� ;

c_c is penalty factor of polluting gases, \$/g ;

N_w is the number of wind turbines.

3.2.4. Constraints of the thermal load dominant mode

1) Equality constraints

Equality constraints of the model include energy flow functions (2)-(5) under the thermal load dominant mode and power balance constraints:

$$P_{L.t} = \sum_{i=1}^{N_{pgu}} P_{pgu.i.t} + \sum_{k=1}^{N_w} P_{w.k.t} + P_{grid.t} \tag{12}$$

$$H_{h.t} + H_{ch.t} = \sum_{i=1}^{N_{pgu}} H_{pgu.i.t} + \sum_{j=1}^{N_a} H_{a.j.t} \tag{13}$$

(12) and (13) are electric power balance and thermal power balance, respectively. Energy loss of the system is neglected.

2) Inequality constraints

Inequality constraints include output constraints of auxiliary boilers and gas turbine:

$$H_{a.j}^{\min} \le H_{a.j.t} \le H_{a.j}^{\max} \tag{14}$$

$$H_{pgu.i}^{\min} \le H_{pgu.i.t} \le H_{pgu.i}^{\max} \tag{15}$$

$$P_{pgu.i}^{\min}(H_{pgu.i.t}) \le P_{pgu.i.t} \le P_{pgu.i}^{\max}(H_{pgu.i.t}) \tag{16}$$

4. ELECTRICAL LOAD DOMINENT MODE and ITS SCHEDULING OPTIMIZATION MODEL

4.1. Energy Flow Function of Electrical Load Dominant Mode

CCHP system operates under electrical load dominant mode preferentially satisfy the real-time balance of electrical load. However, the inherent feasible region of output of gas turbine could lead to the situation that the thermal power output is greater than the thermal load demand. In this paper, thermal storage equipment is out of consideration. It is assumed that the excessive thermal energy is discharged directly into the atmosphere and the maximum thermal load demand of the system can be satisfied by gas fired boiler.

The strategy includes 3 operational situation:

1. When the electrical load demand is less than the maximum output of gas turbine($P_1 < P_{pgu}^{\max}$), electrical load of the system is provided by the output of gas turbine (P_1). The output of wind turbine is 0:

$$P_{w.c} = 0 \tag{17}$$

The output of each generator changes according to various circumstances:

2. If $H_{\text{h}} + H_{\text{ch}} < H_{pgu}^{\max}(P_1)$, the thermal load is satisfied by gas turbine:

$$H_{pgu} = H_{\text{h}} + H_{\text{ch}} \tag{18}$$

3. If $H_{pgu}^{\max}(P_1) \le H_{\text{h}} + H_{\text{ch}}$, the thermal load is mainly satisfied by gas turbine($H_{pgu}^{\max}(P_1)$), and thermal storage is supplemented by auxiliary boiler:

$$H_{\text{a}} = H_{\text{h}} + H_{\text{ch}} - H_{\text{pgu}}^{\max}(P_{\text{pgu}}) \tag{19}$$

4. When the electrical load demand is no less than the maximum output of gas turbine and is smaller than the sum of wind power and maximum output of gas turbine ($P_{pgu}^{\max} \le P_1 < P_{pgu}^{\max} + P_w$), gas turbine operates at maximum electrical output and the electrical load shortage is supplemented by wind turbine:

$$P_{w.c} = P_1 - P_{pgu}^{\max} \tag{20}$$

The output of each generator changes according to various circumstances:

5. If $H_{\text{h}} + H_{\text{ch}} < H_{\text{pgu}}^{\max}(P_{\text{pgu}}^{\max})$, the thermal load demand is completely satisfied by gas turbine:

$$H_{\text{pgu}} = H_{\text{h}} + H_{\text{ch}} \tag{21}$$

6. If $H_{\text{pgu}}^{\max}(P_{\text{pgu}}^{\max}) \le H_{\text{h}} + H_{\text{ch}}$, so that the thermal load is mainly satisfied by gas turbine($H_{pgu}^{\max}(P_{pgu}^{\max})$), and thermal storage is supplemented by auxiliary boiler:

$$H_{\text{a}} = H_{\text{h}} + H_{\text{ch}} - H_{\text{pgu}}^{\max}(P_{\text{pgu}}^{\max}) \tag{22}$$

7. When the electrical load demand is no less than the sum of wind power and maximum output of gas turbine ($P_1 \ge P_{pgu}^{\max} + P_w$), gas turbine operates at maximum electrical output and the wind power is totally sent into the system:

$$P_{\text{w.c}} = P_{\text{w}} \tag{23}$$

The electrical shortage is supplemented by main grid:

$$P_{\text{grid}} = P_1 - (P_{\text{pgu}}^{\max} + P_{\text{w}}) \tag{24}$$

The output of each generator changes according to various circumstances:

1. If $H_{\text{h}} + H_{\text{ch}} < H_{\text{pgu}}^{\max}(P_{\text{pgu}}^{\max})$, the thermal load demand is completely satisfied by gas turbine:

$$H_{\text{pgu}} = H_{\text{h}} + H_{\text{ch}} \tag{25}$$

2. If $H_{\text{h}} + H_{\text{ch}} \ge H_{\text{pgu}}^{\max}(P_{\text{pgu}}^{\max})$, so that the thermal load is mainly satisfied by gas turbine($H_{pgu}^{\max}(P_{pgu}^{\max})$), and thermal storage is supplemented by auxiliary boiler:

$$H_{\text{a}} = H_{\text{h}} + H_{\text{ch}} - H_{\text{pgu}}^{\max}(P_{\text{pgu}}^{\max}) \tag{26}$$

4.2. Economic and Environmentally Friendly Scheduling Optimization Model of Electrical Load Dominant Mode

4.2.1. Objective function

Objective function under electrical load dominant mode is the as (6).

4.2.2. Constraints of the Electrical Load Dominant Mode

1) Equality constraints

Equality constraints of the model include power balance constraints (12), (13), and energy flow functions (17)-(26) under the electrical load dominant mode.

Inequality constraints

Inequality constraints include output constraints of auxiliary boilers (14) and gas turbine under electrical load dominant mode:

$$P_{pgu.i}^{\min} \le P_{pgu.i.t} \le P_{pgu.i}^{\max} \tag{27}$$

$$H_{pgu.i}^{\min}(P_{pgu.i.t}) \le H_{pgu.i.t} \le H_{pgu.i}^{\max}(P_{pgu.i.t}) \tag{28}$$

5. CASE SIMULATION and RESULT ANALYSIS

5.1 Case Study and Parameters

Taking typical days of a certain district as an example, the cool, heat and power load curve are presented in Fig. (**3**).

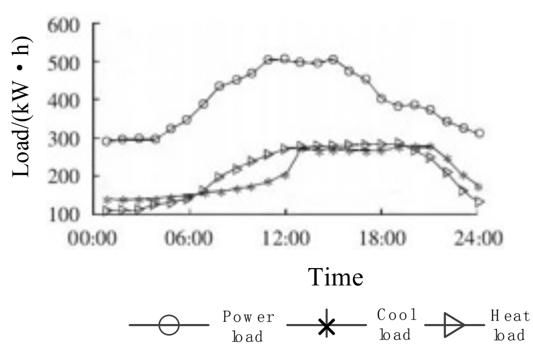

Fig. (3), Typical daily cool, heat and power load curves.

The time-of-use electricity price is as followings: from 6 a.m. to 9 p.m., the price of selling and purchasing power are 0.13, 0.10 \$/(kW•h) , respectively. From 9 p.m. to 6 a.m. next morning, the price of selling and purchasing power are

0.09, 0.05 $\$/(\text{kW}\cdot\text{h})$, respectively. The emission factors of polluting gases are as followings: $\mu_e = 960\text{g/(kW}\cdot\text{h)}$, $\mu_f = 220\text{g/(kW}\cdot\text{h)}$, c_c=0.000003\$/g. The parameters of each power-supply unit can get from reference.

5.2. Simulation Result

The total cost of a CCHP system have difference under the above 2 operational strategies, as illustrated in Fig. (**4**). The environmental cost curve is presented in Fig. (**5**). Table **1** lists different costs during a scheduling period.

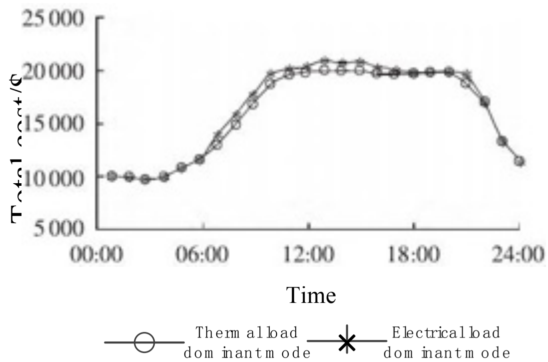

Fig. (4), Total cost curves for different operational strategies.

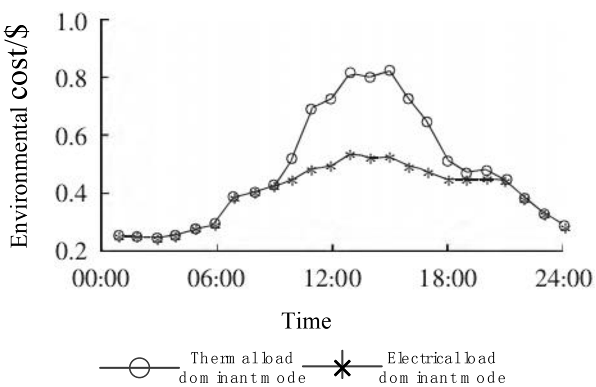

Fig. (5), Environment cost curves for different operational strategies.

Table 1. Schedule-cycle cost for different operational strategies.

Operational Strategy	Total Cost	Power Purchase Cost	Environment Cost	Fuel Cost
Thermal load dominant mode	365941.12	480.16	15.05	365445.91
Electrical load dominant mode	373132.76	253.78	13.09	372865.89

5.3. Result Analysis

As illustrated in Fig. (**4**), operational strategy have a great impact on the economy of the system. From 7 a.m. to 10 p.m., total cost of the system operated under electrical load dominant mode is evidently higher than that of another mode. However, from 11 p.m. to 6 a.m. next morning, the total cost of the system operated under these 2 strategies are quite basic. It is because that both of these 2 strategies can provide enough cool, heat and power load to the system, and there is no thermal output or electrical output surplus during the process.

As can be seen from Fig. (**5**), from 9 a.m. to 9 p.m., environment cost of the system operated under thermal load dominant mode is greater. The reason is that thermal load demand and power purchase cost increase a lot during the time, which could increase environment cost of the system.

Make a detailed analysis of Table **1**, it can be concluded that total cost of the system operated under thermal load dominant mode is lower than that of another mode, which means the economy of the system is improved. However, since that the system operated under electrical load dominant mode preferentially meets electrical load demand and the power purchase from the connected main grid is limited, power purchase cost of this mode is lower. That means system operated under this mode has less dependence on the main grid, and consequently, the system has less impact on the main grid. Apparently, for the reason that the thermal load dominant mode relies heavily on the main grid, power purchase cost increases a lot. Moreover, the penalty factor of generating electricity far outweighs the penalty factor of burning natural gas ($\mu_e = 960\text{g/(kW}\cdot\text{h)}, \mu_f = 220\text{g/(kW}\cdot\text{h)}$). Therefore, environment cost of thermal load dominant mode is greater under the circumstances.

CONCLUSION

Analyzing energy flow of cooling, heating and power in detail and taking the real-time balance of energy flow into account, the paper proposes an useful conception-energy flow function, which could reflect the real-time balance of electricity accurately. Furthermore, energy flow functions of the system operated under electrical load dominant mode and thermal load dominant mode are established, which could be the research foundation of optimization scheduling of CCHP systems.

Taking the energy flow function as its energy balance equality constraint, an optimal economic and environmental dispatch model is built, which includes the fuel cost, power purchase cost and pollution emission penalty as environmental cost in its objective function. From the results, it can be seen that the proposed energy flow function and model enhances the energy utilization level, reduces the productive cost and improves the environmental efficiency.

Simulation results show that the system operated under thermal load dominant mode has prominent economy, whereas the power purchase cost is higher and the impact on main grid is greater. In comparison, the system operated under electrical load dominant mode has significant environmental benefits. The CCHP system adjusts its optimal operation scheme according to its operational strategy.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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