EFFICIENCY AND BENEFIT EVALUATION OF MULTI-ENERGY MICROGRID CONSIDERING MULTI-TYPE HEAT PUMP

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Abstract

With the advancement of China's comprehensive energy services, the multi-energy microgrid has become more and more popular. As a typical substitution of electric energy, the heat pump has remarkable social and economic benefits in the multi-energy microgrid. In order to better develop comprehensive energy services, it is of vital importance to evaluate the efficiency and benefit of the microgrid. In this paper, the differences of several types of heat pumps are considered, and a day-ahead economic dispatch model for electric-thermal-gas microgrid is established. From the technical and economic perspectives, some indicators to measure the efficiency and benefit of multi-energy microgrid are then proposed. Case studies of a typical park-level multi-energy microgrid shows that these indicators can reflect the effect of heat pump on the efficiency and benefit of multi-energy microgrid. In addition, case studies also draw a conclusion that the heat pump can improve the rate of energy utilization and the economics of microgrid operation, and different types of heat pumps have different effects in improving the efficiency and benefit of multi-energy microgrid.

1 Introduction

Multi-energy microgrid is a new energy supply system integrating multiple energy sources, which is an important part of the Urban Energy Internet. Compared with traditional microgrid, multi-energy microgrid contains variety types of energy such as electricity, heat, cold, gas, hydrogen and so on. The energy conversion device inside the multi-energy microgrid can realize interconnection of various energy sources, thereby improving the system reliability and the energy efficiency, which has very important value for building a resource-saving and environment-friendly society [1].

In order to meet the new trend of energy development, China's State Grid is gradually transforming into a comprehensive energy service provider [2]. Comprehensive energy service is a new energy service to cater to the diversification of energy production and consumption of end customers, covering energy planning and design, engineering investment and construction, multi-energy operation services, investment and financing services, etc. As an energy terminal, multi-energy microgrid is the physical subject of comprehensive energy service implementation. Detailed research on multi-energy microgrid is helpful for the development of comprehensive energy service.

Recently, many researchers have studied on the planning of multi-energy systems. In [3], a two-stage mixed integer linear programming method for regional multi-energy system planning considering the integration of distributed renewable energy is proposed. In [4], considering physical restrictions on networks and environmental issues, a framework is proposed to optimize the design and size of interconnected energy hubs. In [5], considering the security of multi-energy microgrid, a new mixed integer linear optimization model is proposed, which determines the best combination of technologies, scale, layout and related scheduling.

From another point of view, attention has also been paid to the operation of multi-energy systems. In [6], the microgrid joint scheduling problem of multi-energy systems is regarded as a rolling layer Markov decision processes (MDP), and the problem of large state space and decision-making space of MDP is solved by roll-out algorithm. In [7], a two-stage coordinated operation method is proposed to optimize and coordinate the combined cooling, heating and power plants, flexible electricity, heat load and thermal storage under multiple uncertain conditions. In [8], a control method using robust optimization technology is proposed, especially the energy flow distribution and storage inside the energy hub are determined to meet the time-varying output requirements of the energy hub while minimizing the energy consumption. In [9], a robust operation optimization framework based on two-stage iterative modelling is proposed, which is suitable for intelligent cells with multi-energy devices and integrated energy networks.

In addition, some scholars have also conducted research about multi-energy system evaluation. In [10], considering different heating scenarios, a method to measure the influence of gas network on the flexibility of power system is proposed. In [11], an economic evaluation method based on Monte Carlo simulation for multi-energy systems is proposed.

However, relevant research on multi-energy microgrid evaluation is still relatively lacking, especially the evaluation indicator system to measure the performance of multi-energy microgrid has not yet been established. Quantitative evaluation indicators can better realize the comparison between multi-energy microgrids, and the influence of various factors on the implementation effect of multi-energy microgrid can be found. It will promote the development of multi-energy microgrid, and help comprehensive energy service providers to provide customers with better comprehensive energy services.

The aim of this paper is to establish an evaluation indicator system for multi-energy microgrid, and to evaluate and analyse the characteristics of multi-energy microgrid from various aspects. The rationality and scientificity of the evaluation indicator system are verified through case studies, and this system will provide a reference for the planning and operation of multi-energy microgrid.

The remaining of this paper is organized as below. Section 2 introduces overview of multi-type heat pump. Model and method of multi-energy microgrid operation are proposed in Section 3. Evaluation indicator system for multi-energy microgrid is presented in Section 4. Section 5 demonstrates experimental results of a typical multi-energy microgrid. In Section 6, Conclusions are arrived at.

2 Overview of multi-type heat pump

Heat pump is an energy saving device that transfers thermal energy from low-temperature heat source to high-temperature heat source. Heat pump can make full use of thermal energy in nature to realize high efficiency cooling and heating, and it will not pollute the environment during operation. Therefore， heat pump technology is also a clean and renewable energy utilization technology [12].

2.1 Rationale of heat pump

Depending on the second law of thermodynamics, heat can spontaneously transfer from a high-temperature object to a low-temperature object, but cannot spontaneously proceed in the opposite direction. The rationale of a heat pump is to force heat to flow from a low-temperature object to a high-temperature object in a reverse circulation mode. The heat pump only consumes a small amount of reverse circulation net work to obtain a large amount of heat supply, and can effectively utilize low-grade thermal energy which is difficult to apply, thus achieving the purpose of energy conservation.

The structure of different types of heat pumps is almost the same, which can be seen in Fig. 1 [13]. Heat pump has two operating states: heating state in winter and cooling state in summer. When heat pump is in the heating state, the working principle is described as follows [14]. The thermal energy exchanged by the heat exchanger from the natural heat source is firstly transferred to the evaporator through the circulation of the working medium. Next, the liquid working medium at the other end absorbs the heat in the evaporator and is converted to the gaseous working medium. Under the action of compressor, working medium changes from the state of low temperature and low pressure to the state of high temperature and high pressure, and then transfers the heat to condenser. Finally, the gaseous working medium emits heat in the condenser, converts the heat from the gaseous state to the liquid state, and returns to the evaporator through the throttle valve to start the next circulation, and the heat released in the condenser is transferred to the heat pipe of multi-energy microgrid. When heat pump is in the cooling state, the working principle is similar to that in the heating state.

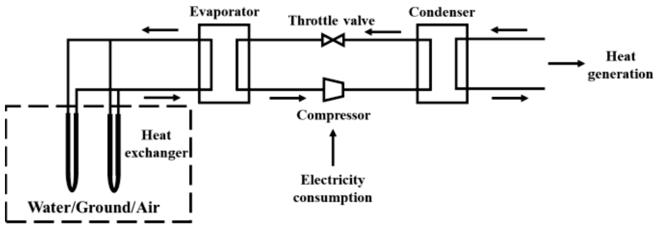

Fig. 1 Structure of heat pump

2.2 Modelling of heat pump

In principle, the high-grade heat output by heat pump is essentially low-grade heat from natural environment. However, heat pump can be regarded as an electrothermal conversion component with electric energy as input and thermal energy as output in order to facilitate practical analysis. The heating efficiency of the heat pump can be described by the coefficient of performance (COP), and COP denotes the ratio of the heat produced to the effective input power under the rated conditions of the heat pump. In general, actual heating efficiency of the heat pump can be approximately equal to the COP. In other words, the output heat power can be approximated as a linear function of the input electrical power, which can be expressed as

$$P_h^{HP}\left(t\right)=\eta_h^{HP}P_e^{HP}\left(t\right) \tag{1}$$

where $P_h^{HP}\left(t\right)$ and $P_e^{HP}\left(t\right)$ are the heating power and input electrical power of the heat pump at time slot t ; η_h^{HP} is the heating efficiency of the heat pump.

In addition, the constraint of output of heat pump can be satisfied, which is given in

$$u^{HP}\left(t\right)P_h^{HP\min}\le P_h^{HP}\left(t\right)\le u^{HP}\left(t\right)P_h^{HP\max} \tag{2}$$

where $u^{HP}\left(t\right)$ represents the working condition of the heat pump at time slot t , which is a binary variable; $P_h^{HP\min}$ and $P_h^{HP\max}$ are the minimal and maximal heating power of the heat pump, respectively.

2.3 Characteristics of multi-type heat pump

According to different low-temperature heat sources, heat pumps can be divided into water source heat pumps (WSHPs), ground source heat pumps (GSHPs) and air source heat pumps (ASHPs) [15]. The characteristics of these three types of heat pumps can be summarized in Table 1.

WSHPs utilize low-grade thermal energy resources formed by solar energy and geothermal energy absorbed by groundwater, rivers and lakes. Compared with soil and air, water has the largest specific heat capacity and the best heat transfer performance, so the heat efficiency of WSHPs is the highest. However, WSHPs also have some disadvantages. On the one hand, the geographical position of WSHPs is relatively limited and must be installed near the water source. On the other hand, WSHPs have higher requirements on the water source used, and the cost difference of different water source utilization is quite large.

GSHPs mainly use solar energy and geothermal energy absorbed by soil to form low-grade thermal energy resources. Since the specific heat capacity of soil is between water and air, the heating efficiency of GSHPs is between WSHPs and ASHPs. Compared with WSHPs, the installation position of GSHPs is more flexible, but similar to WSHPs, GSHPs have high requirements on the ground. Besides, the cost of GSHP is relatively high, because GSHPs need to dig a well underground.

ASHPs use energy in air to generate thermal energy. the heating efficiency of ASHPs is the lowest compared with that of WSHPs and GSHPs, because of smallest specific heat capacity of air. The biggest problem of ASHPs is that outdoor air temperature has great influence on the operation efficiency. The main advantage of ASHPs is lower investment cost.

Table 1 Characteristics of different type heat pump

Type	Efficiency	Cost	Merit	Demerit
WSHP	4.3-5.0	High	Very high efficiency	High water requirement
GSHP	4.0	Very high	High efficiency	High soil requirement
ASHP	3.0	Low	Low cost	Low efficiency

3 Analysis of multi-energy microgrid

In this paper, multi-energy microgrid is an electric-thermal-gas energy interconnection microgrid, which is connected to the distribution network and the gas network. The multi-energy microgrid includes renewable energy power generation component, energy conversion components and energy storage components. The renewable energy power generation component is photovoltaic (PV) power generation. The energy conversion components include the heat pump, the combined heat and power (CHP) system and the gas boiler. The energy storage components include battery storage, thermal storage and gas storage. The dispatch scheme for multi-energy microgrid is seen in Fig. 2.

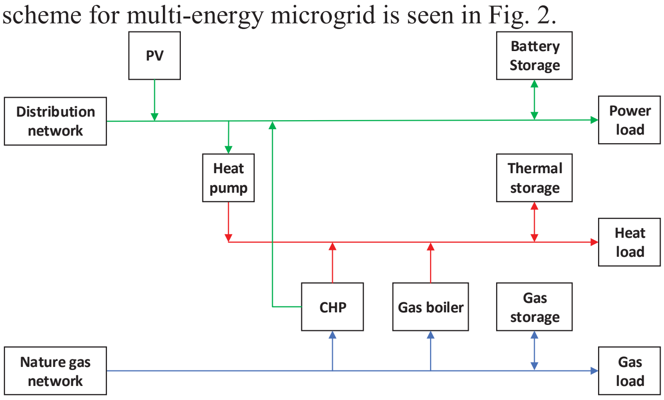

Fig. 2 Dispatch scheme for multi-energy microgrid

3.1 Day-ahead dispatch model for multi-energy microgrid

The objective of multi-energy microgrid day-ahead dispatch model is to minimize the total cost, which includes the payment for electricity and nature gas.

$$\min \quad C_{total} = \sum_{t=1}^{T}\left[c_{DN}(t)P_e(t) + c_{GN}(t)P_g(t)\right] \tag{3}$$

In Equation (3), $c_{DN}(t)$ and $c_{GN}(t)$ are prices of electricity and nature gas, respectively; $P_e(t)$ signifies the power purchase from distribution network, and $P_g(t)$ from nature gas network.

The constraints include system, components and networks [16, 17].

3.1.1 Multi-energy balance constraints: During the whole dispatch process, the demand and supply of multiple energy including electricity, heating and nature gas should be balanced, as expressed in the following equations:

$$\begin{cases} P_e(t) + P_e^{PV}(t) - P_e^{HP}(t) + P_e^{CHP}(t) + P_e^{BS}(t) = L_e(t) \\ P_h^{HP}(t) + P_h^{CHP}(t) + P_h^{GB}(t) + P_h^{TS}(t) = L_h(t) \\ P_g(t) - P_g^{CHP}(t) - P_g^{GB}(t) + P_g^{GS}(t) = L_g(t) \end{cases} \tag{4}$$

where $P_e^{PV}(t)$ is the power of the PV injected into multi-energy microgrid at time slot t; $P_e^{CHP}(t)$, $P_h^{CHP}(t)$ and $P_g^{CHP}(t)$ are the electrical power, the heating power and input nature gas power of the CHP system at time slot t, respectively; $P_h^{GB}(t)$ and $P_g^{GB}(t)$ are the heating power and input nature gas power of the gas boiler at time slot t; $P_e^{BS}(t)$, $P_h^{TS}(t)$ and $P_g^{GS}(t)$ are the net power of the battery storage, the thermal storage and the gas storage injected into multi-energy microgrid, respectively; $L_e(t)$, $L_h(t)$ and $L_g(t)$ are power load, heat load and gas load at time slot t.

3.1.2 PV power constraint: The output power of PV panels is mainly affected by light intensity, so it is difficult to control. When the output power of PV panels is too high, it can be allowed to curtail to ensure security in multi-energy microgrid, which can be expressed as follows:

$$0 \le P_e^{PV}(t) \le P_e^{PVfore}(t) \tag{5}$$

where $P_e^{PVfore}(t)$ is the forecast value of PV output power at time slot t.

3.1.3 CHP system constraints: The CHP system can generate electricity and heat meanwhile, and the relationship between the output and the input of the CHP system can be expressed as below:

$$P_e^{CHP}(t) = \eta_e^{CHP} P_g^{CHP}(t) \tag{6}$$

$$P_h^{CHP}(t) = \eta_h^{CHP} P_g^{CHP}(t) \tag{7}$$

where η_e^{CHP} and η_h^{CHP} represent the electrical and heating efficiency of the CHP system, respectively.

The output constraints should also be satisfied

$$u^{CHP}(t) P_e^{CHP\min} \le P_e^{CHP}(t) \le u^{CHP}(t) P_e^{CHP\max} \tag{8}$$

where $u^{CHP}(t)$ denotes the working condition of the CHP system at time slot t, which is a binary variable; $P_e^{CHP\min}$ and $P_e^{CHP\max}$ are respectively the minimal and maximal electrical power of the CHP system,.

3.1.4 Gas boiler constraints: The gas boiler can inject the heating power generated by natural gas into multi-energy microgrid. The heating power of the gas boiler can be formulated as follows:

$$P_h^{GB}(t)=\eta_h^{GB}P_g^{GB}(t) \tag{9}$$

where η_h^{GB} is the heating efficiency of the gas boiler.

The output of gas boiler should be limited within a range.

$$u^{GB}(t)P_h^{GB\min}\le P_h^{GB}(t)\le u^{GB}(t)P_h^{GB\max} \tag{10}$$

where $u^{GB}(t)$ is a binary variable, which is the working condition of the gas boiler at time slot t; $P_h^{GB\min}$ and $P_h^{GB\max}$ are respectively the minimal and maximal heating power of the gas boiler.

3.1.5 Battery storage constraints: The battery storage has three typical work conditions. $u_e^{ch}(t)$ and $u_e^{dis}(t)$ are binary variables, which are used to describe these work conditions of the battery storage, as shown in Table 2.

Table 2 The relationship between values of binary variables and working condition

$u_e^{ch}(t)$	$u_e^{dis}(t)$	Working condition
1	1	/
1	0	Charging
0	1	Discharging
0	0	Standing by

The constraints of power of the battery storage are expressed by the following equations:

$$0\le P_e^{ch}(t)\le u_e^{ch}(t)P_e^{ch\max} \tag{11}$$

$$0\le P_e^{dis}(t)\le u_e^{dis}(t)P_e^{dis\max} \tag{12}$$

where $P_e^{ch}(t)$ and $P_e^{dis}(t)$ are the charging and discharging power of the battery storage, respectively; $P_e^{ch\max}$ and $P_e^{dis\max}$ are the maximal charging and discharging power of the battery storage, respectively.

The battery storage cannot work in charging and discharging conditions at the same time, so this constraint can be considered.

$$u_e^{ch}(t)+u_e^{dis}(t)\le 1 \tag{13}$$

The state of energy (SOE) of the battery storage should be within a certain range, as shown in

$$E_e^{\min}\le E_e(t)\le E_e^{\max} \tag{14}$$

where $E_e(t)$ is the SOE of the battery storage at time slot t. $E_e^{\min}$ and $E_e^{\max}$ are the minimal and maximal SOE of the battery storage, respectively.

The SOE of the battery storage is related to its previous state and related efficiency, which can be described as

$$E_e(t+1)=E_e(t)+\left[P_e^{ch}(t)\eta_e^{ch}-\frac{P_e^{dis}(t)}{\eta_e^{dis}}\right]\Delta T \tag{15}$$

where η_e^{ch} and η_e^{dis} are the charging and discharging efficiency of the battery storage; ΔT is the time interval.

To ensure the continuous operation of the battery storage, the energy balance should be kept in a full operation period, which can be expressed as

$$E_e(0)=E_e(T) \tag{16}$$

where $E_e(0)$ is the initial SOE of the battery storage; $E_e(T)$ denotes the SOE of the battery storage at time slot T.

The net power of the battery storage at each time slot can be formulated as

$$P_e^{BS}(t)=P_e^{dis}(t)-P_e^{ch}(t) \tag{17}$$

The constraints of thermal storage and gas storage are similar, which will not be presented again.

3.1.6 Upstream networks constraints: The power purchase from distribution network and nature gas network should be no more than its limit. These constraints are expressed by the following equations:

$$0\le P_e(t)\le P_e^{\max} \tag{18}$$

$$0\le P_g(t)\le P_g^{\max} \tag{19}$$

where $P_e^{\max}$ and $P_g^{\max}$ are the maximal power purchase from distribution network and nature gas network, respectively.

Besides, the constraints of heat pump in Section 2.2 belong to the day-ahead dispatch model.

3.2 Operation simulation of multi-energy microgrid

The operation simulation method is usually used to analyse multi-energy system. According to different time scales, operation simulation can be divided into daily, monthly and annual operation simulation. The operation simulation process of multi-energy microgrid is illustrated in Fig. 3.

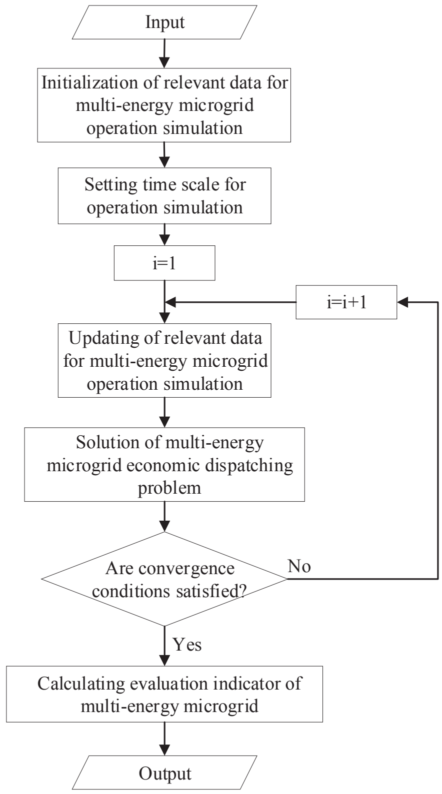

Fig. 3 Operation simulation of multi-energy microgrid

4 Evaluation indicators for multi-energy microgrid

Different from traditional microgrid, multi-energy microgrid have more complex relationship between multi-energy carriers. Therefore, evaluation indicators for multi-energy microgrid are more diverse. In this paper, an evaluation indicator system from two aspects of efficiency and benefit is established according to characteristics of multi-energy microgrid operation. The specific evaluation indicator system is illustrated in Fig. 4.

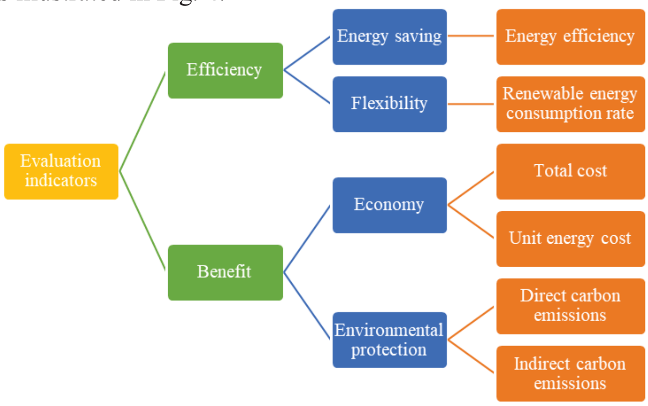

Fig. 4 Evaluation indicator system for multi-energy microgrid

4.1 Efficiency

In this paper, energy saving and flexibility can be used to reflect efficiency of multi-energy microgrid. Energy saving indicates that the same load demand can be met by less energy supply in multi-energy microgrid. Flexibility shows that the multi-energy microgrid can adapt to more complex and extreme scenarios.

4.1.1 Energy saving: Energy saving indicates show that energy loss is as little as possible in the process of energy transmission and conversion, and more energy is utilized by customers. For multi-energy microgrid, energy efficiency indicator is proposed to show energy saving. Energy efficiency refers to the ratio of energy that customers can effectively utilize to energy injected into multi-energy microgrid. The formula for energy efficiency is as follows:

$$\eta^{utilize}=\frac{\sum_{t=1}^{T}\left[L_e(t)+L_h(t)+L_g(t)\right]}{\sum_{t=1}^{T}\left[P_e(t)+P_g(t)+P_e^{PV}(t)\right]}\times 100\% \tag{20}$$

4.1.2 Flexibility: Flexibility of energy system is mainly manifested in multiple ways to achieve efficient use of energy. With the development of renewable energy, renewable energy curtailment has become a serious problem. An energy system is more flexible, there are more ways to consume renewable energy. Therefore, renewable energy consumption rate is a key indicator to measure flexibility of multi-energy microgrid, which can be described as the following equation.

$$\eta^{consumption}=\frac{\sum_{t=1}^{T}P_e^{PV}(t)}{\sum_{t=1}^{T}P_e^{PVfore}(t)}\times 100\% \tag{21}$$

4.2 Benefit

In this paper, economy and environmental protection can be used to reflect benefit of multi-energy microgrid. Economy is measured by the operation cost of multi-energy microgrid. Environmental protection is embodied in the environmentally friendly operation of multi-energy microgrid.

4.2.1 Economy: Economy of multi-energy microgrid can be mainly measured by total cost and unit energy cost, which are from the perspective of overall and individual, respectively.

(1) Total cost: Total cost can well reflect the overall economic benefit of the operation of multi-energy microgrid, which can be expressed as:

$$C_{total}=\sum_{t=1}^{T}\left[c_{DN}(t)P_e(t)+c_{GN}(t)P_g(t)\right] \tag{22}$$

(2) Unit energy cost: Unit energy cost can reflect the cost of various kinds of energy utilized by customers, which can be divided into unit electricity cost, unit heat cost and unit gas cost.

$$C_e=\frac{\sum_{t=1}^{T}\left\{c_{DN}(t)\left[P_e(t)-P_e^{HP}(t)\right]+c_{GN}(t)P_{ge}^{CHP}(t)\right\}}{\sum_{t=1}^{T}\left[L_e(t)\right]} \tag{23}$$

$$C_h=\frac{\sum_{t=1}^{T}\left\{c_{DN}(t)P_e^{HP}(t)+c_{GN}(t)\left[P_{gh}^{CHP}(t)+P_g^{GB}(t)\right]\right\}}{\sum_{t=1}^{T}\left[L_h(t)\right]} \tag{24}$$

$$C_g=\frac{\sum_{t=1}^{T}\left\{c_{GN}(t)\left[P_g(t)-P_g^{CHP}(t)-P_g^{GB}(t)\right]\right\}}{\sum_{t=1}^{T}\left[L_g(t)\right]} \tag{25}$$

where C_e, C_h and C_g are unit electricity cost, unit heat cost and unit gas cost, respectively; $P_{ge}^{CHP}(t)$ and $P_{gh}^{CHP}(t)$ represent the electrical power and the heating power converted according to the proportional relationship of the CHP system, respectively. The expressions of $P_{ge}^{CHP}(t)$ and $P_{gh}^{CHP}(t)$ are as follows:

$$P_{ge}^{CHP}(t)=\frac{\eta_e^{CHP}}{\eta_e^{CHP}+\eta_h^{CHP}}P_g^{CHP}(t) \tag{26}$$

$$P_{gh}^{CHP}(t)=\frac{\eta_h^{CHP}}{\eta_e^{CHP}+\eta_h^{CHP}}P_g^{CHP}(t) \tag{27}$$

4.2.2 Environmental protection: In this paper, environmental protection mainly considers carbon emissions, because global warming is becoming increasingly serious. Direct carbon emissions and indirect carbon emissions are chosen to reflect carbon emissions.

(1) Direct carbon emissions: Direct carbon emissions refer to carbon emissions generated in the process of energy transmission and conversion of multi-energy microgrid.

$$Q_{CO_2}^{direct}=\sum_{t=1}^{T}\varepsilon_g\left[P_g^{CHP}(t)+P_g^{GB}(t)\right]\Delta T \tag{28}$$

where ε_g is carbon emission coefficient of nature gas consumption. In this paper, the value of ε_g is 0.0196.

(2) Indirect carbon emissions: Indirect carbon emissions refer to carbon emissions generated from energy purchased from upstream networks, which can be written as follows:

$$Q_{CO_2}^{indirect} = \sum_{t=1}^{T} \varepsilon_e P_e(t) \Delta T \tag{29}$$

where ε_e is carbon emission coefficient of electricity production.

5 Case studies

In the case studies, a typical multi-energy microgrid is given as an example, which is seen in Fig. 2. In this multi-energy microgrid, parameters of energy conversion components and energy storage components are shown in Tables 3 and 4. The maximal power purchase from distribution network and nature gas network is 500kW. The curves of multi-energy load and PV power are demonstrated in Fig. 5. The curves of prices of electricity and nature gas are shown in Fig. 6.

In order to test the influence of different type heat pump on the multi-energy complementary implementation of multi-energy microgrid, 4 scenarios are proposed in this paper, which are seen in Table 5.

The operation simulation period is 24 hours, and the time granularity is 1 hour. The program is developed using MATLAB R2017a. The optimization solver is CPLEX 12.8.0 [18].

By solving the day-ahead dispatch model for multi-energy microgrid, we can obtain dispatching results of multi-energy microgrid in a day, and dispatching results of multi-energy microgrid in Scenario 2 are demonstrated in Fig. 7, 8 and 9. According to evaluation indicator system for multi-energy microgrid in Section 4, we can also calculate the corresponding evaluation indicators in each scenario, which are seen in Table 6 and 7.

Table 3 Parameters of energy conversion components

Component	Maximum power (kW)	Minimum power (kW)	Efficiency
WSHP	100	20	5.0
GSHP	100	20	4.0
ASHP	100	20	3.0
CHP	200	20	0.3(E)/ 0.4(H)
Gas boiler	100	0	0.9

Table 4 Parameters of energy storage components

Storage	Maximum energy (kWh)	Minimum energy (kWh)	Maximum charging/ discharging power (kW)	charging/ discharging efficiency
Battery storage	100	30	40	0.85
Thermal Storage	300	90	40	0.90
Gas Storage	582	0	145.5	0.95

Table 5 Heat pump type in multi-energy microgrid in different scenarios

Scenario	Heat pump
Scenario 1	/
Scenario 2	WSHP
Scenario 3	GSHP
Scenario 4	ASHP

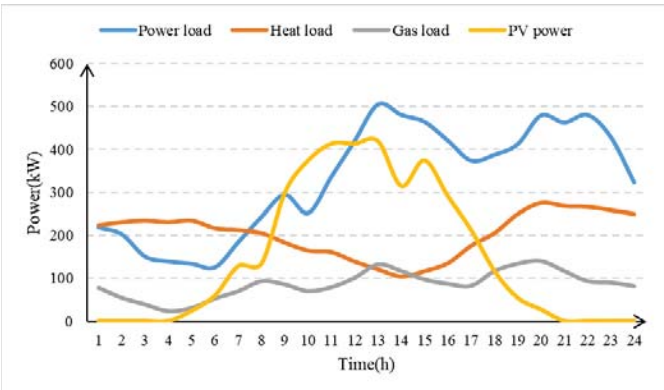

Fig. 5 Forecasted multi-energy load and PV power

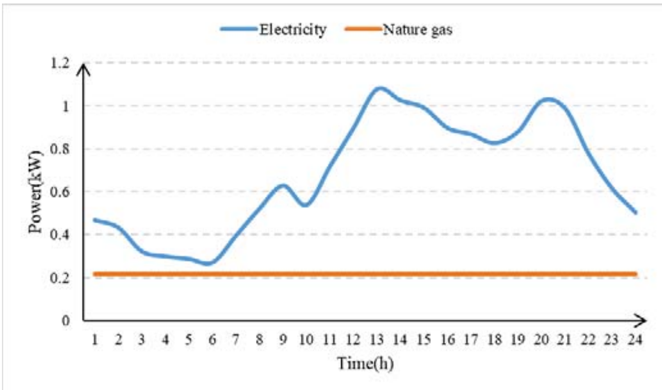

Fig. 6 Prices of electricity and nature gas

The dispatching results of the electrical power is shown in Fig. 7. Power load is mainly met by electricity purchased from the distribution network and generated by the CHP system and PV panels. Due to the large PV installed capacity of multi-energy microgrid, there may be curtailment of PV power at noon. When electricity price is too high, such as 12-17 h, power load is mainly met by electricity generated by the CHP system and PV panels, because electricity generated by the CHP system is cheaper than that purchased from the distribution network and PV output is sufficient. In the evening, power load is high and the PV power is not output, power load is mainly met by electricity purchased from the distribution network and the generated by the CHP system.

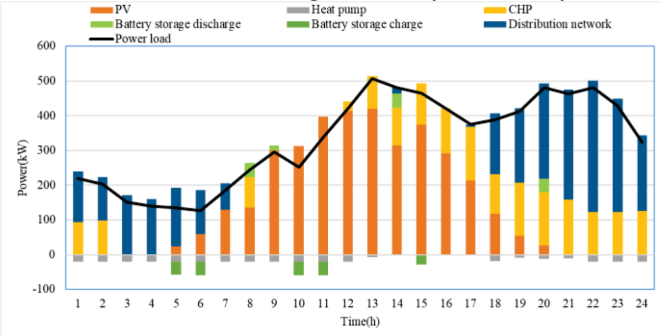

Fig. 7 Day-ahead dispatch of multi-energy microgrid in Scenario 2 (the electrical power)

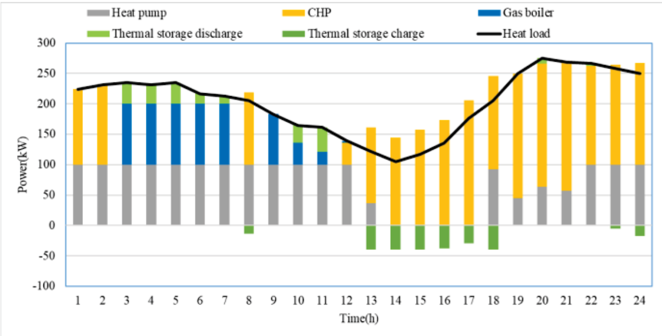

Fig. 8 Day-ahead dispatch of multi-energy microgrid in Scenario 2 (the heating power)

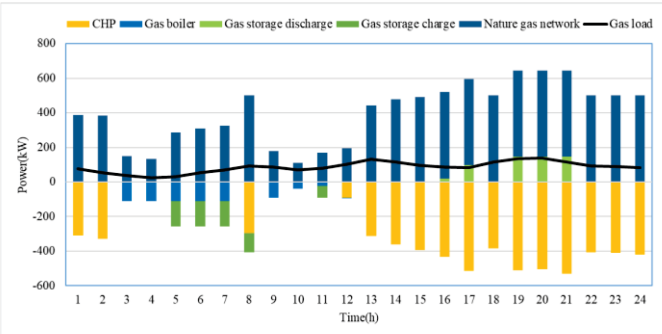

Fig. 9 Day-ahead dispatch of multi-energy microgrid in Scenario 2 (the gas power)

The dispatching results of the heating power is shown in Fig. 8. When there is a heat pump in the multi-energy microgrid, the base load of heat is carried by the heat pump in most time slots. But in certain time slots, such as 14-17 h, heat load is met by heat generated by the CHP system, because electricity price is high and heat load is low. The gas boiler mainly generates heat in 3-7 h, because power load is low and the heating efficiency of the gas boiler is higher than that of the CHP system. The thermal storage is mainly responsible for peak cutting and valley filling of heat load. When heat load is low, such as 13-18 h, the thermal storage will charge excess thermal energy. When heat load is high, such as 3-7 h, the thermal storage will discharge thermal energy.

The dispatching results of the gas power is shown in Fig. 9. Gas load is met by natural gas purchased by the nature gas network. In addition, natural gas is also used as fuel for the CHP system and the gas boiler to participate in heating and power supply.

Efficiency of multi-energy microgrid is shown in Table 6. Energy efficiency and renewable energy consumption rate of multi-energy microgrid with heat pump has greatly increased. The higher the heating efficiency of the heat pump is, the higher the energy efficiency of multi-energy microgrid is. However, renewable energy consumption rate will decrease with the increase of the heating efficiency of the heat pump, because the heat pump with lower heating efficiency will consume more electric energy in order to produce the same thermal energy.

Benefit of multi-energy microgrid is listed in Table 7. Total cost of multi-energy microgrid with heat pump is greatly reduced, and that of Scenario 2 is the lowest. Unit energy cost of multi-energy microgrid with heat pump is also decreased. For unit electricity cost, the addition of heat pump makes it unnecessary for the CHP system to operate every time slot, so that the electricity purchased from distribution system can be used more by customers when electricity price is low, thus reducing unit electricity cost. Because of the high efficiency of heat pump, the unit heat cost is reduced. The unit gas cost is roughly constant because it is affected by the loss of nature gas by the gas storage and the operation situation of the gas storage is similar among all scenarios. Direct carbon emissions are mainly carbon emissions that natural gas produce in the process of energy conversion. Since the heat pump replaces the heat output of the gas boiler and the CHP system, direct carbon emissions will be greatly reduced. However, the heat pump needs to consume a large amount of electric energy, resulting in an increase in the purchase of electricity from the distribution network, which means indirect carbon emissions will increase. In this paper, the results of indirect carbon emissions are not shown in detail, because carbon emission coefficient of electricity production is related to the local power source structure.

All in all, the addition of heat pump can effectively improve the efficiency and benefit of multi-energy microgrid. The higher the efficiency of heat pump is, the better the overall effect of multi-energy complementary implementation in multi-energy microgrid is. For the actual investment, the type of heat pump should be chosen according to the specific situation, because the characteristics of different types of heat pumps are different.

Table 6 Efficiency of multi-energy microgrid in 4 scenarios

Scenario	Energy efficiency	Renewable energy consumption rate
Scenario 1	84.89%	91.53%
Scenario 2	95.76%	97.84%
Scenario 3	94.39%	98.11%
Scenario 4	92.76%	98.56%

Table 7 Benefit of multi-energy microgrid in 4 scenarios

Scenario	Total cost (Yuan)	Unit electricity cost (Yuan/kWh)	Unit heat cost (Yuan/kWh)	Unit gas cost (Yuan/kWh)	Direct carbon emissions (kg)
Scenario 1	4311.24	0.3101	0.2856	0.2228	190.5004
Scenario 2	3847.70	0.2845	0.2322	0.2228	135.6289
Scenario 3	3887.63	0.2823	0.2440	0.2228	139.6320
Scenario 4	3945.12	0.2790	0.2612	0.2228	144.5734

6 Conclusions

In this paper, a multi-energy microgrid day-ahead economic dispatch model is established considering the characteristics of different types of heat pumps. From the technical and economic point of view, the evaluation indicators of multi-energy microgrid efficiency and benefit are proposed from four aspects of energy saving, flexibility, economy and environmental protection. Taking a typical park-level multi-energy microgrid as an example, the proposed evaluation indicator system is used to evaluate the effect of multi-energy complementary implementation of multi-energy microgrid with different types of heat pumps. It is found that the addition of heat pump can effectively improve the energy saving, flexibility, economy and environmental protection of the operation of multi-energy microgrid. Higher efficiency heat pump can make the effect of multi-energy complementary implementation in multi-energy microgrid better overall. In short, a clean and efficient energy conversion component can improve the efficiency and benefit of multi-energy microgrid and promote comprehensive energy service providers to provide more high-quality comprehensive energy services.

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