

Emission Trading Based Optimal Scheduling Strategy of Energy Hub with Energy Storage and Integrated Electric Vehicles

Yanhong Luo, Xinwen Zhang, Dongsheng Yang, and Qiuye Sun

Abstract—This paper focuses on the optimal scheduling of the district energy system with multiple energy supply modes and flexible loads. For multi-energy system (MES), the energy hub (EH) model including energy storage system and integrated electric vehicle (EV) is established. Based on the model, the influence of pollutant trading market on total operation cost is analyzed, and the optimal scheduling strategy is further put forward to realize the minimum purchase cost and emission tax cost of the MES. Finally, this paper compares the economic benefit of the fixed mode and the response mode, and discusses the contribution of the energy storage device and the multi-energy complementary mode to energy utilization efficiency. The simulation results indicate that optimal scheduling strategy of the EH can coordinate various energy complementary modes reasonably. Meanwhile, the proposed strategy is able to improve the operation economy of the EH, and ensure the better response effect of the demand side. The sensitivity analysis demonstrates the impact of pollutant emission price change on emission reduction.

Index Terms—Energy hub (EH), demand response, electric vehicle (EV), energy storage, emission trading, operation optimization.

I. INTRODUCTION

DUE to the rapid development of social economy, large-scale usage of fossil energy has led to a series of problems in the past decades, such as the exhaustion of traditional energy, environmental pollution and global climate deterioration [1]. The development and introduction of clean and renewable energy sources have become a feasible way to solve these problems due to the advantages such as low emissions and sustainability. Current research has applied green renewable energy to smart road and additional lighting to realize energy sustainability [2], [3]. Moreover, the implementation measures of renewable sources as alternative sources of elec-

tricity are studied in [4]. At the same time, the new technologies of information communication, control and energy integration have given rise to a new energy utilization system – Energy Internet. Integrated energy system (IES) is the main carrier of the Energy Internet at the physical level, which can integrate the supply of renewable clean energy and traditional energy, while scheduling the adjustable loads on the demand side. And the energy hub (EH) is the main integrated presentation form of IES [5]. The energy interconnection form of multi-energy complementarity improves the energy efficiency by virtue of the complementary conversion between traditional fossil energy and renewable energy [6].

Recently, IES has become the gateway of multi-energy integration. Experts and scholars from different countries are vigorously developing IES in the context of Energy Internet, such as the FREEDM system developed by the US National Science Foundation [7], the E-Energy program led by Germany [8], the UK demonstration project in Manchester, the Future Internet for Smart Energy (FINSNEY) project launched by the European Union [9], etc. In May 2014, the first distributed multi-energy system in China was put into operation with a total installation capacity of 87 MW.

Some achievements have been made in IES research, mainly focusing on system modeling [11], [13], [15], [16], [21], [22], capacity addressing [10], [17], [20], economic operation [12], [14], [18], [19] and other aspects. Reference [15] established a mixed-integer linear programming to plan the capacity of photovoltaic (PV) power generation and battery energy storage in a nanogrid. Reference [16] combined the supply characteristics of the EH with the load-side flexibility of the demand-side management, and modelled the heat demand based on the thermodynamic principle. Reference [17] proposed a two-layer control strategy, which distributes the power output of electricity and heat according to the proportion of capacity. Reference [18] proposed a distributed consistent alternating multiplier method to solve the optimal management problem of Energy Internet. Reference [19] proposed the optimal control strategy for power flow management of microgrid with battery, renewable energy and electric vehicle (EV) in rolling horizon. Reference [22] proposed a standardized modeling method for multi-energy

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Y. Luo (corresponding author), X. Zhang, D. Yang and Q. Sun are with the School of Information Science and Engineering, Northeastern University, Shenyang 110004, China (e-mail: luoyanhong@ise.neu.edu.cn; 1770491@stu.neu.edu.cn; yangdongsheng@mail.neu.edu.cn; sunqiuye@ise.neu.edu.cn).

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systems.

Existing research has actively explored the optimal operation of EHs in IES with demand response. Usually, the overall modeling of EHs is considered, and the energy flow direction inside the EH is less restricted. At the same time, the consumption patterns of fossil energy as the main energy source have brought about a series of environmental pollution and climate problems [23]. In view of the above problems based on the existing research, the major contributions of this paper are presented as follows:

1) This paper constrains some energy flow in the IES to reduce the cost of line reconstruction and the influence of the bidirectional energy flow on the power grid.

2) The scheduling adjusts the flexible cold, heat and electric loads by using the demand response strategy. And the load adjustment under the user's comfort desire will be considered. A large number of EVs and energy storage equipment are connected to the grid, promoting the flexibility on the demand side. This paper considers two modes of accessing the grid for integrated EVs. The comparative analysis of the integrated demand response scheduling of the users is also an innovation point of this paper.

3) The above studies have already investigated the carbon emissions of multi-energy sources [24]. There are few studies on the impact of other greenhouse gases on multi-energy optimization, and we consider the emissions of CO_2 , NO_x and SO_x . Some studies have shown that, although energy storage devices play an important role in the access of renewable energy, there are still drawbacks of CO_2 emissions. This paper also takes into account the emissions of energy storage devices.

II. MODELING OF EH

The EH considering demand response includes energy generation, conversion, and storage devices. Among them, the energy generation includes grid power, natural gas and PV power generation. The energy conversion device comprises combined cooling, heating, and power (CCHP) system, which is composed of a gas turbine (GT), a heat recovery boiler (HRB) and an absorption chiller (AC), and the other is a gas boiler (GB) and an electric chiller (EC) for energy conversion. The energy storage device includes energy storage and heat storage device, and the user side is mainly involved in demand response by EVs, hot water load, and air conditioning. In order to encourage the construction of distributed energy, the redundant power of PV peak hours can be sold to the grid company to obtain certain benefits. Each equipment adjusts its own energy supply and energy use plan through the information of electricity price, gas price and unit emission tax of the dispatch center. The structure of the EH system designed in this paper is shown in Fig. 1, where ES represents energy storage and HS represents heat storage.

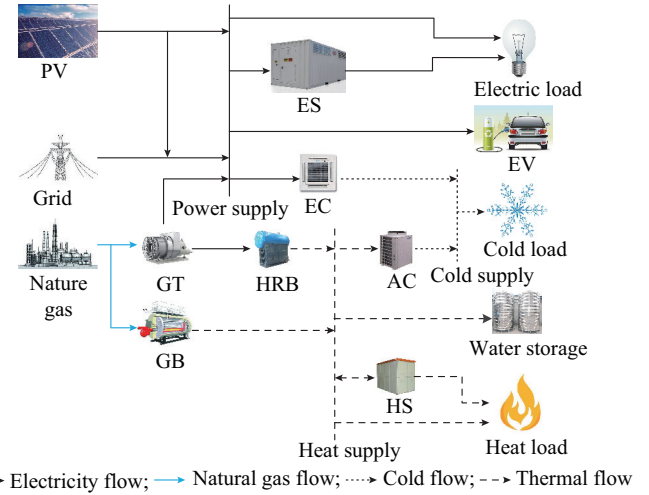


Fig. 1. Structure of EH.

A. Energy Generators

1) CCHP

This paper considers the GT as the generation system for CCHP. It is assumed that the efficiency of the GT in the operation interval remains. The output is expressed as:

$$P_t^{GT} = \eta^{GT} \lambda_{gas} f_t^{GT} / \Delta T \quad (1)$$

where P_t^{GT} is the electric power output; f_t^{GT} is the amount of gas consumption; λ_{gas} is the heating value of natural gas; η^{GT} is the power generation efficiency; and ΔT is the scheduling duration.

The HRB can recycle the waste heat generated by the GT, and the recovered heat power expression is:

$$H_t^{GT} = \eta^{WH} (1 - \eta^{GT}) \lambda_{gas} f_t^{GT} / \Delta T \quad (2)$$

where H_t^{GT} is the thermal power recovered by HRB; and η^{WH} is the recovery efficiency for HRB.

The residual heat generated by CCHP when outputting electric power is converted by HRB and AC. The expressions of electric, thermal and cold output power of CCHP are as follows:

$$P_t^{CCHP} = P_t^{GT} = \eta^{GT} \lambda_{gas} f_t^{GT} / \Delta T \quad (3)$$

$$H_t^{CCHP} = P_t^{CCHP} \eta^{WH} (1 - \eta^{GT}) / \eta^{GT} - H_t^{AC} \quad (4)$$

$$C_t^{CCHP} = H_t^{AC} \eta^{AC} \quad (5)$$

where P_t^{CCHP} is the electric output power of CCHP at time t ; H_t^{AC} is the thermal power input of AC at time t ; H_t^{CCHP} and C_t^{CCHP} are the thermal power output and the cold power output of CCHP at time t , respectively; and η^{AC} is the efficiency of AC.

2) GB

GB is a commonly used heat generation equipment. The thermal power output of GB is:

$$H_t^{GB} = f_t^{GB} \eta^{GB} \lambda_{gas} / \Delta T \quad (6)$$

where H_t^{GB} is the thermal power output of GB; f_t^{GB} is the amount of natural gas; and η^{GB} is the efficiency of GB.

3) PV

As a clean energy source, PV system has gradually be-

come a promising distributed energy source. Its output power depends on the intensity of solar radiation. Its output electric power expression is [25]:

$$P_t^{PV} = \eta_{PV} SI [1 - 0.005(\theta_t^{out} - 25)] \quad (7)$$

where P_t^{PV} is the maximum output power of PV at time t ; η_{PV} is the efficiency of PV generation; S is the PV array area; I is the solar radiation; and θ_t^{out} is the outdoor temperature.

B. ES Devices

1) ES

According to the guidance of time-of-use electricity price, the ES can be charged during the off-peak demand, and discharged during the on-peak demand. The expression for its state of charge (SOC) is:

$$S_{t+1}^{ES} = S_t^{ES} + \frac{P_t^{ES, ch} \eta^{ES, ch} \Delta T}{\Omega_{ES}} - \frac{P_t^{ES, dis} \Delta T}{\eta^{ES, dis} \Omega_{ES}} \quad (8)$$

where S_t^{ES} is the SOC of ES at time t ; $P_t^{ES, ch}$ and $P_t^{ES, dis}$ are the charging power and discharging power of ES at time t , respectively; $\eta^{ES, ch}$ and $\eta^{ES, dis}$ are the charging efficiency and discharging efficiency of ES, respectively; and Ω_{ES} is the capacity of ES.

2) HS

The HS can temporarily store the thermal power added by GT of CCHP unit due to the electric power generated by it and the thermal power generated by GB. The heat of HS can be expressed as:

$$W_{t+1}^{HS} = W_t^{HS} + H_t^{HS, ch} \eta^{HS, ch} \Delta T - \frac{H_t^{HS, dis} \Delta T}{\eta^{HS, dis}} \quad (9)$$

where W_t^{HS} is the energy content of HS at time t ; $H_t^{HS, ch}$ and $H_t^{HS, dis}$ are the charging heat and discharging heat of HS at time t , respectively; and $\eta^{HS, ch}$ and $\eta^{HS, dis}$ are the heat storage efficiency and release efficiency of HS, respectively.

C. Flexible Response Loads

In the EH, in addition to the basic cold, heat and power loads that meet users' demands, the demand side also has flexible loads with responsiveness.

1) EV

The charging pile of EV can adjust the charging rate of EV by receiving the command of the dispatching center. The SOC of EV can be expressed as:

$$S_{t+1, k}^{EV} = S_{t, k}^{EV} + P_{t, k}^{EV, ch} \eta_k^{EV, ch} \Delta T / E_k^{EV} \quad (10)$$

where $S_{t, k}^{EV}$ is the SOC of the k^{th} EV at time t ; $P_{t, k}^{EV, ch}$ is the charging power of the k^{th} EV at time t ; $\eta_k^{EV, ch}$ is the charging efficiency; and E_k^{EV} is the battery capacity of the k^{th} EV.

2) Hot Water Load

The hot water load can be maintained in a certain temperature range according to the user's expectation to ensure the user's hot water supply. When a certain amount of hot water is consumed by the user, it will be injected with the same amount of cold water as the hot water consumed. According to the second law of thermodynamics, the calculation formula

of the water temperature is:

$$\theta_{t+1}^{ws} = \frac{V_t^{cold} (\theta_t^{cw} - \theta_t^{ws}) + V \theta_t^{ws}}{V} + \frac{H_t^{ws} \Delta T}{VC_w} \quad (11)$$

where θ_t^{ws} is the water storage temperature at time t ; θ_t^{cw} is the temperature of cold water injected into the water storage; V_t^{cold} and V are the volumes of injected cold water at time t and the water storage, respectively; and H_t^{ws} is thermal power provided to the water storage device at time t .

3) Air Refrigeration System

The indoor air cooling load can be satisfied by the cold power generated by the AC in the CCHP unit and the EC. Indoor temperature change is related to the outdoor temperature, the ability of building materials to transfer heat and the cold power supplied by the EH, the temperature at time t can be expressed as:

$$\theta_{t+1}^{in} = \theta_t^{in} e^{-\Delta T/\tau} + (-RH_t^{air} \Delta T + \theta_t^{out})(1 - e^{-\Delta T/\tau}) \quad (12)$$

where θ_t^{in} and θ_t^{out} are the indoor and outdoor temperatures at time t , respectively; $\tau = RC$; R is the thermal resistance of the house shell; C is the heat capacity of air; and H_t^{air} is the cold power of the chiller at time t .

III. OPTIMIZATION FORMULATION

A. Objective Function

The EH considers the day-optimized scheduling problem and rationally arranges the output of each unit at each time interval. The dispatching center aims to minimize the sum of the cost of purchasing power, natural gas and the cost of pollutant discharge transaction. The objective function is:

$$\min C = C_G + C_P + F \quad (13)$$

$$C_G = \sum_t \pi^G \left(\frac{P_t^{CCHP}}{\eta_{GT}} + \frac{H_t^{GB}}{\eta_{GB}} \right) \frac{\Delta T}{\lambda_{gas}} \quad (14)$$

$$C_P = \sum_t (\pi_t^{TOU} P_t^{PG} - \pi_t^S P_t^S) \Delta T \quad (15)$$

where C_G , C_P and F are the costs of purchasing gas, electricity and pollutants, respectively; π^G , π_t^{TOU} and π^S are the price of purchasing gas, the time-of-use electricity price and the price of selling electricity, respectively; and P_t^{PG} and P_t^S are the purchasing power and selling power at time t , respectively. Among them, the electricity sales only include electricity produced by new energy resources.

B. Pollutant Trading Function

The CO₂ emissions from electric energy consumption account for a large proportion of the country, causing irreparable damage and pollution to the environment. These emissions are mainly from natural gas and coal-fired generation units. The greenhouse gases produced are mainly CO₂, NO_x and SO_x. Conventions control carbon emissions through carbon trading, and allocate carbon emission quotas to their carbon sources in relation to their electricity consumption and power generation. If the carbon emissions exceed the quota in the production and use of energy, it is necessary to pur-

chase the excess amount from the carbon trading market at the carbon trading price of the current day. For other greenhouse gases emitted by EH, this paper considers NO_x and SO_x that have a greater impact on the environment. There is no free allocation of these emissions, and they are directly purchased according to the local pollutant discharging transaction price. This paper only considers the emission of natural gas and electricity. The pollutant generated by PV generation is negligible, so that clean energy can be used to prioritize the use of clean energy. The expression of free carbon emission quotas allocated by the market is:

$$E_t^p = P_t^{PG} E_{PG} + P_t^{CCHP} E_{CCHP} + H_t^{GB} E_{GB} \quad (16)$$

where E_{PG} , E_{CCHP} and E_{GB} are the unit carbon emission quota coefficients of each energy supply equipment of power grid purchase, CCHP power generation and GB heating, respectively.

The actual carbon emissions of energy supply are determined by the electricity and natural gas consumption, and the calculation is as follows:

$$E_t^A = P_t^{PG} E_p + (f_t^{GT} + f_t^{GB}) E_G \quad (17)$$

where E_t^A is the total amount of carbon emissions in the energy supply at time t ; and E_p and E_G are the unit carbon emission coefficients of electricity and natural gas, respectively.

It has been found that battery ES has become a new source of emissions, which has a certain impact on the environment. This paper introduces the calculation of greenhouse gases generated during the discharge process of battery ES devices.

$$E_t^S = P_t^{ES,dis} E_S \quad (18)$$

where E_S is the unit carbon emission coefficient of ES, which is 91.33 g/kWh in this paper.

The total carbon emission of the EH is:

$$E_t^{Total} = E_t^p + E_t^A + E_t^S \quad (19)$$

Other types of pollutants are also generated in the energy supply and have an impact on the environment. This paper considers the emissions of NO_x and SO_x from electricity consumption and natural gas consumption, and control their emissions through the cost of pollutants. The actual emissions of these pollutants are calculated in terms of electricity and natural gas consumption, and the expression is:

$$E_t^R = P_t^{PG} (E_{NO_x}^p + E_{SO_x}^p) + (f_t^{GT} + f_t^{GB}) (E_{NO_x}^G + E_{SO_x}^G) \quad (20)$$

where $E_{NO_x}^p$ and $E_{SO_x}^p$ are the unit greenhouse gas emission coefficients of NO_x and SO_x , respectively, when the EH consumes power; and $E_{NO_x}^G$ and $E_{SO_x}^G$ are the unit greenhouse gas emission coefficients of NO_x and SO_x , respectively, when the EH consumes natural gas.

Then the daily fee that needs to be paid to the pollutant trading market is calculated as:

$$F = \sum_t \left[(E_t^{Total} - E_t^p) F_{CO_2} + E_t^R F_{NO_x, SO_x} \right] \quad (21)$$

where F_{CO_2} and F_{NO_x, SO_x} are the CO_2 emission price of the ex-

cess part and the emission prices of other pollutants, respectively.

IV. DEMAND-SUPPLY BALANCES AND OPERATION CONSTRAINTS

A. Demand-supply Balances

1) Electrical Power Balance

$$P_t^{PG} - P_t^S + P_t^{PV} + P_t^{CCHP} = P_t^L + \sum_k P_{t,k}^{EV, ch} + P_t^{ES, ch} - P_t^{ES, dis} + P_t^{EC} \quad (22)$$

$$P_t^{ES, dis} = \lambda^L P_t^L \quad (23)$$

where P_t^L is the basic power load; and λ^L is the coefficient within the interval of $[0, 1]$, which represents the proportion of the electric power provided by the power storage equipment for the base load.

2) Thermal Balance

$$H_t^{GB} + H_t^{CCHP} = H_t^L + H_t^{HS, ch} - H_t^{HS, dis} + H_t^{ws} + H_t^{AC} \quad (24)$$

where H_t^L is the basic heat load at time t .

3) Cooling Balance

$$C_t^{CCHP} \cdot COP_{AC} + E_t^{EC} \cdot COP_{EC} = H_t^{air} \quad (25)$$

where E_t^{EC} is the output cooling power of EC at time t ; and COP_{AC} and COP_{EC} are the refrigerating coefficients of AC and EC, respectively. In this paper, $COP_{AC} = 0.7$ and $COP_{EC} = 3$.

B. Operation Constrains

1) System Operation Constraints

$$0 \leq P_t^{PG} \leq P_{\max}^{PG} \quad (26)$$

$$0 \leq f_t^{GT} + f_t^{GB} \leq f_{\max}^{gas} \quad (27)$$

where $P_{\max}^{PG}$ and $f_{\max}^{gas}$ are the maximum values of the power purchase and gas purchase, respectively. Formulas (26) and (27) define the maximum values of power purchase and gas capacity of EH, respectively.

2) EV Constraints

$$S_{k, \min}^{EV} \leq S_{t,k}^{EV} \leq S_{k, \max}^{EV} \quad (28)$$

$$P_{t,k}^{EV} = 0 \quad t \notin [t_k^{ari}, t_k^{dep}] \quad (29)$$

$$S_{dep,k} \geq S_{k, \min} + d_k^{dri} / d_{k, \max} \quad (30)$$

$$0 \leq P_{t,k}^{EV, ch} \leq P_{k, \max}^{EV} \quad (31)$$

where $S_{k, \min}^{EV}$ and $S_{k, \max}^{EV}$ are the maximum and minimum values of the SOC of the k^{th} EV battery, respectively; t_k^{ari} and t_k^{dep} are the times when the EV arrives and disconnects the power system, respectively, which define the schedulable time period of the EV; $S_{dep,k}$ is the SOC of the trip distance, which can be satisfied when the k^{th} EV leaves the power system; and $d_{k, \max}$ and $P_{k, \max}^{EV}$ are the maximum endurance mileage and maximum charging power of the k^{th} EV, respectively.

3) ES Constraints

$$S_{\min}^{ES} \leq S_t^{ES} \leq S_{\max}^{ES} \quad (32)$$

$$0 \leq P_t^{ES, ch} \leq u_t^{ES, ch} P_{\max}^{ES, ch} \quad (33)$$

$$0 \leq P_t^{ES,dis} \leq u_t^{ES,dis} P_{\max}^{ES,dis} \quad (34)$$

where $S_{\min}^{ES}$ and $S_{\max}^{ES}$ are the maximum and minimum values of the SOC of ES, respectively; $P_{\max}^{ES,ch}$ and $P_{\max}^{ES,dis}$ are the maximum charging power and discharging power of ES, respectively; and $u_t^{ES,ch}$ and $u_t^{ES,dis}$ are binary variables representing the charging and discharging states of ES at time t , respectively. Formula (32) is the SOC constraint of ES, and (33) and (34) are the charging and discharging power constraints.

In order to ensure the continuity of the optimal scheduling, and ES cannot charge and discharge at the same time, the following constraints are met:

$$u_t^{ES,ch} + u_t^{ES,dis} \leq 1 \quad (35)$$

$$S_1^{ES} = S_T^{ES} \quad (36)$$

4) HS Constraints

$$W_{\min}^{HS} \leq W_t^{HS} \leq W_{\max}^{HS} \quad (37)$$

$$0 \leq H_t^{HS,ch} \leq u_t^{HS,ch} H_{\max}^{HS,ch} \quad (38)$$

$$0 \leq H_t^{HS,dis} \leq u_t^{HS,dis} H_{\max}^{HS,dis} \quad (39)$$

$$u_t^{HS,ch} + u_t^{HS,dis} \leq 1 \quad (40)$$

$$W_1^{HS} = W_T^{HS} \quad (41)$$

where $W_{\max}^{HS}$ and $W_{\min}^{HS}$ are the maximum and minimum values of HS, respectively; $H_{\max}^{HS,ch}$ and $H_{\max}^{HS,dis}$ are the maximum injection power and release power of HS, respectively; and $u_t^{HS,ch}$ and $u_t^{HS,dis}$ are binary variables representing the states of injecting and drawing heat of HS at time t , respectively.

5) User Comfort Constraints

$$\theta_{\min}^{in} \leq \theta_t^{in} \leq \theta_{\max}^{in} \quad (42)$$

where $\theta_{\min}^{in}$ and $\theta_{\max}^{in}$ are the upper and lower limits of the indoor temperature, respectively. Formula (42) is kept within the comfort temperature range desired by the user.

$$\theta_{\min}^{ws} \leq \theta_t^{ws} \leq \theta_{\max}^{ws} \quad (43)$$

where $\theta_{\min}^{ws}$ and $\theta_{\max}^{ws}$ are the upper and lower limits of the water temperature, respectively, to ensure that the user has hot water available throughout the day.

6) Operation Constraints of CCHP and GB

$$0 \leq P_t^{GT} \leq P_{\max}^{GT} \quad (44)$$

$$0 \leq H_t^{GT} \leq H_{\max}^{GT} \quad (45)$$

$$0 \leq H_t^{GB} \leq H_{\max}^{GB} \quad (46)$$

$$|P_t^{GT} - P_{t-1}^{GT}| \leq \Delta P_{\max}^{GT} \quad (47)$$

where $P_{\max}^{GT}$ and $H_{\max}^{GT}$ are the maximum power and heat output values of GT, respectively; $H_{\max}^{GB}$ is the maximum heat output of GB; and $\Delta P_{\max}^{GT}$ is the maximum climbing value of GT. Formulas (44)-(46) limit the output of each energy generation device, and (47) is the climbing limit of GT.

C. Another Charging Mode of EVs

When integrated EVs do not participate in a demand response project, once an EV is connected to the grid, it is charged at a constant maximum power until the battery reaches the upper limit of the battery capacity. The SOC of

the EV (10) is replaced by (48):

$$S_{t+1,k}^{EV} = S_{t,k}^{EV} + P_{k,\max}^{EV} \eta_k^{EV,ch} \Delta T / E_k^{EV} \quad (48)$$

The constraint conditions are also modified as follows:

$$S_{dep,k} = S_{\max}^{ES} \quad (49)$$

Formulas (28), (29) and (49) compose the new constraints.

V. SIMULATION RESULTS

A. Optimized Operation Results

The electric-gas-heat-combined EH optimization scheduling model proposed in this paper takes a multi-energy district as an example. Its structure and components are shown in Fig. 1. EH contains two hundred EVs with the same specification. This paper does not consider the loss during the energy transfer process, but takes the schedule of a typical day in summer as an example. The solar radiation and outdoor temperature are shown in Fig. 2.

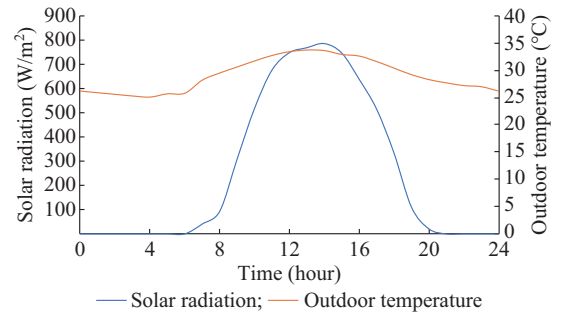


Fig. 2. Solar radiation and temperature on a typical day in summer.

The basic power and heat demand on a typical day in summer is shown in Fig. 3. The battery capacity of an EV is 18 kW, and the time of its arrival and departure from the charging station follows a normal distribution, e. g., $t_k^{ari} \sim N(8, 4^2)$, $t_k^{dep} \sim N(18, 4^2)$. The initial SOC value of EV obeys a uniform distribution $S_{1,k}^{EV} \sim (0.3, 0.5)$. The expected travelling distance of the users follows a lognormal distribution $\ln d_k^{dri} \sim N(2.2, 0.88^2)$. The maximum endurance mileage $d_{k,\max}$ is 100 km. The park implements peak and valley electricity prices for industries. The rush hours are 11:00-13:00, 16:00-17:00, when the electricity price is 1.2011 CNY/kWh. The peak hours are 10:00-11:00, 13:00-15:00, 18:00-21:00, when the electricity price is 1.0994 CNY/kWh. The flat hours are 7:00-10:00, 15:00-16:00, 17:00-18:00, and 21:00-23:00, when the electricity price is 0.7510 CNY/kWh. The valley hours are 23:00-7:00, when the electricity price is 0.4126 CNY/kWh. The sold electricity price is 1.15 CNY/kWh. The price of natural gas is 2.83 CNY/m³. The emission price of carbon trading market is 57 CNY/t. The emission price of pollutant trading market is 5000 CNY/t. The unit scheduling time is one hour, with 24:00-1:00 being the first time period, and so on. The final time period is 24. Other specific parameters are shown in Tables I and II.

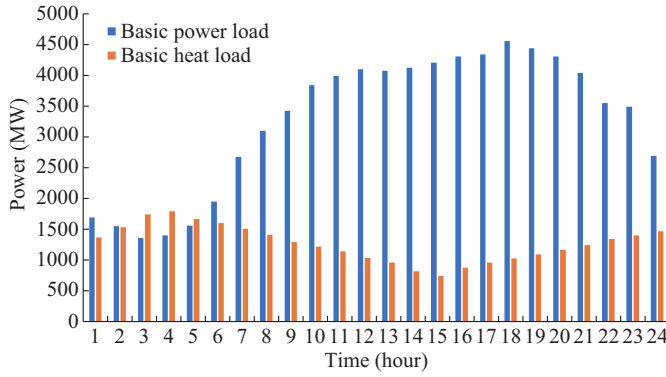


Fig. 3. Basic power and heat load on a typical day in summer.

TABLE I
PARAMETERS OF EH MODEL

Parameter	Value	Parameter	Value
λ_{gas}	9.97 kWh/m ³	θ^{cw}	15 °C
η^{GT}	35%	V	150 L
η^{WH}	85%	E_{PG}	798 g/kWh
η^{AC}	90%	E_{CCHP}	424 g/kWh
η^{GB}	90%	E_{GB}	152 g/kWh
η^{PV}	15.7%	E_P	968 g/kWh
Ω_{ES}	2 MW	E_G	220 g/m ³
$\eta^{ES, ch}, \eta^{ES, dis}$	95%	$E_{NO_x}^P$	0.5 g/kWh
$\eta^{HS, ch}, \eta^{HS, dis}$	90%	$E_{SO_x}^P$	2.1 g/kWh
E_k^{EV}	18 kW	$E_{NO_x}^G$	0.019 g/m ³
$\eta_k^{EV, ch}$	90%	$E_{SO_x}^G$	2.62×10^{-4} g/m ³

TABLE II
PARAMETERS OF EH CONSTRAINTS

Parameter	Value	Parameter	Value
P_{max}^{PG}	5 MW	$P_{max}^{ES, ch}, P_{max}^{ES, dis}$	0.3 MW
f_{max}^{gas}	500 m ³	$H_{max}^{HS, ch}, H_{max}^{HS, dis}$	0.5 MW
$S_{k, min}^{EV}$	0.2	θ_{min}^{in}	23 °C
$S_{k, max}^{EV}$	0.9	θ_{max}^{in}	25 °C
$P_{k, max}^{EV}$	3 kW	θ_{min}^{ws}	60 °C
S_{min}^{ES}	0.25	θ_{max}^{ws}	80 °C
S_{max}^{ES}	0.95	P_{max}^{GT}	2 MW
W_{min}^{HS}	0.5 MW	H_{max}^{GB}	4 MW
W_{max}^{HS}	2 MW	ΔP_{max}^{GT}	0.3 MW

The range of indoor temperature and water temperature is the comfort range satisfactory to the user. The initial indoor temperature is 25 °C and the water temperature is 70 °C. The initial SOC value of the ES is 0.3, and the initial heat storage of the HS is 1 MW. The change of the hot water tank according to the time of injection of cold water is shown in Fig. 4.

The EH optimization scheduling model established in this paper is a typical mixed-integer linear programming problem. In this paper, the model is built based on the YALMIP platform language in MATLAB environment, and the GUR-

OBI solver is called to obtain the optimal solution. In order to verify the effectiveness of multi-energy complementary, demand response and pollutant emission control in the EH, this paper designs a comparative analysis of different scenarios. The scenario construction is shown in Table III.

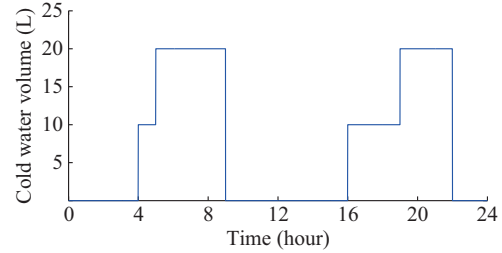


Fig. 4. Volume of cold water.

TABLE III
SCENARIO DESIGN

Scenario	Multi-energy complement	Demand response	ES	Emission trading
1	✓	✓	✓	✓
2	✓	✓	✓	
3	✓	✓		
4				

Scenario 1 is the optimal scheduling model established in this paper. The optimization results are shown in Fig. 5. The curve in Fig. 5 is the basic power load curve.

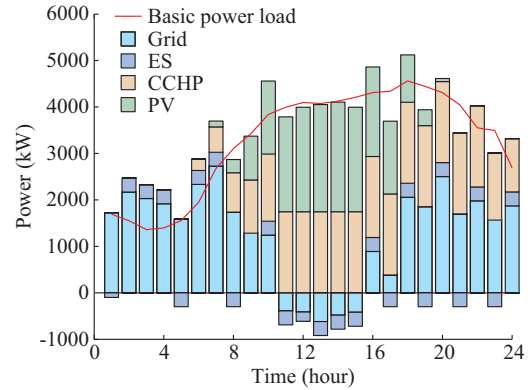


Fig. 5. EH optimization results for scenario 1.

Combined with the analysis of time-of-use electricity price, the optimization results show that due to the energy storage device, integrated EVs and demand-side response, the district purchases less power during rush and peak hours of electricity price, and sells excess power to the grid during peak hours of PV generation. When the load is present upward trend, the EH of the district reflects the advantages of multi-energy complementarity. CCHP and PV generation bear part of the energy demand, except that CCHP operates at almost the maximum capacity during the valley price period and the flat section, thereby reducing the purchase of electricity and the emissions of pollutant.

As shown in Fig. 6, the change of the SOC value of ES is that it is charged during the periods of low electricity price and low power consumption, and discharged during the peak periods of power consumption, alleviating the pressure of the grid. The HS also makes the operation of CCHP more efficient and the remaining recovered heat of CCHP is stored when the heat demand is low. Figure 7 shows the changes of indoor temperature and water temperature in scenario 1. According to the results, the water temperature and indoor temperature follow the range expected by the users well. During the peak period of electricity price, the CCHP unit runs, and the cooling demand is mainly supplied by the cooling output of CCHP, and is cooled by the EC for the rest of the time.

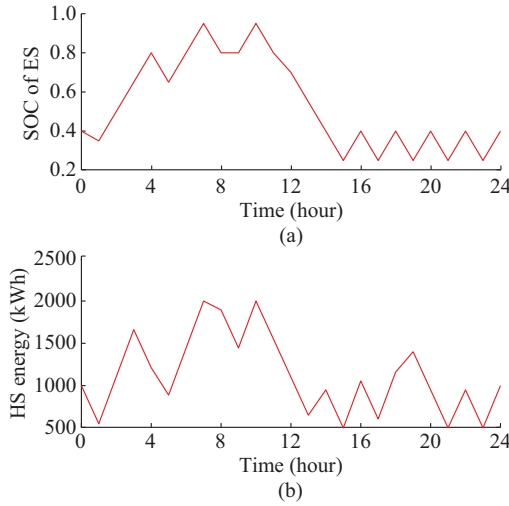


Fig. 6. State changes of ES and HS devices. (a) ES. (b) HS.

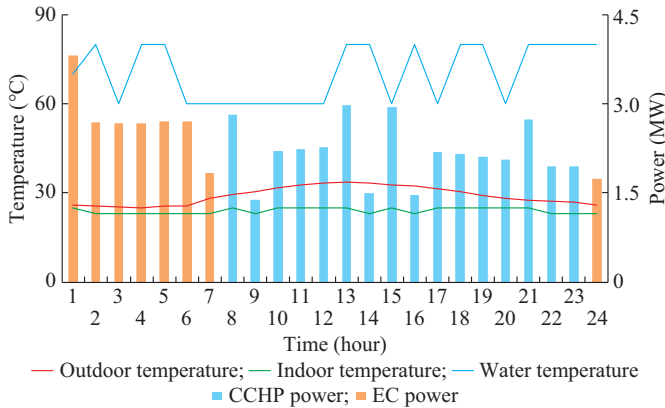


Fig. 7. Temperature changes in scenario 1.

Scenario 2 does not consider the emission trading strategy, and does not charge the pollutants. The results show that the actual carbon emissions without considering emission trading is 35.1747 t, which is 1.2395 t more than scenario 1. Carbon emissions increase by 3.65%, while emissions of other pollutants increase by 3.32%. Scenario 1 costs more than scenario 2 because pollution costs are not taken into account. It can be seen that the optimization strategy considering pollutant trading can effectively reduce the emission of pollutants.

Scenario 3 does not include energy storage equipment. Scenario 4 does not adopt multi-energy complementary mode. Each energy system operates separately. The electric load demand is supplied by the grid purchase, PV power generation and GT generation. The heat load demand is satisfied by GB, and the cold demand is satisfied by the EC. The response load does not participate in the interaction. It is replaced by the basic load. The system does not contain energy storage equipment, and does not charge for pollutant emissions. Scenario 4 is regarded as a reference model for other scenarios.

Figure 8 shows the power purchase curves for the four scenarios. As can be seen from Fig. 8 and Table IV, the district had purchased more electricity without limiting pollutant emissions. Scenario 1 consumes less power and produces less emissions than scenario 2. Compared with scenario 3, scenario 1 purchases more electric power stored in EH during the valley period. Although the total purchased power of scenario 3 is slightly smaller than that of scenario 1, scenario 1 sells more electricity. Therefore, the operation cost of the system is much smaller than that of scenario 3. As a reference model for other examples, scenario 4 has much higher operation costs, purchased power, and pollutant emissions than other scenarios. Due to thermal power generation, the purchased power closely follows the demand for electricity, and its operation cost is much higher than that of scenario 1, reaching up to 9.9%, which verifies the economics of this optimization strategy.

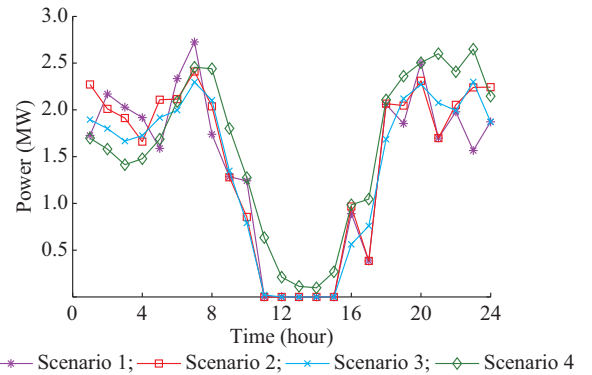


Fig. 8. Power purchase curves in four scenarios.

TABLE IV
SIMULATION RESULTS OF EACH SCENARIO

Scenario	Operation cost (CNY)	Purchase power (MW)	Carbon emission (t)	Other emission (t)
1	41957	33.5609	33.9352	0.0874
2	41763	34.6741	35.1747	0.0903
3	43396	33.2006	33.8309	0.0865
4	46119	38.0494	38.3010	0.0991

Figure 9 shows the participation of EVs in demand response regulation. It can be seen that the charging transfer of EVs during peak and valley periods verifies the effective-

ness of the demand response strategy.

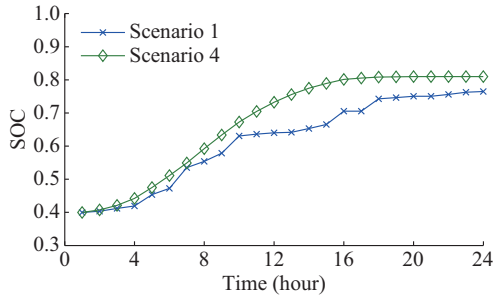


Fig. 9. Average SOC curve of EV.

B. Sensitivity Analysis

In order to analyze the impact of pollutant trading price on the optimal operation results of EH, carbon emissions account for a large proportion in the pollutant discharging system. Considering the impact of changes in carbon tax on operational results, there are two types namely grid-connected type and off-grid type. The grid-connected type is the optimized operation strategy considered in the paper, as in scenario 1, and the off-grid type is the scenario where the demand side and the grid have no power exchange. Meanwhile, there is no energy storage device. The comparison results are shown in Figs. 10 and 11.

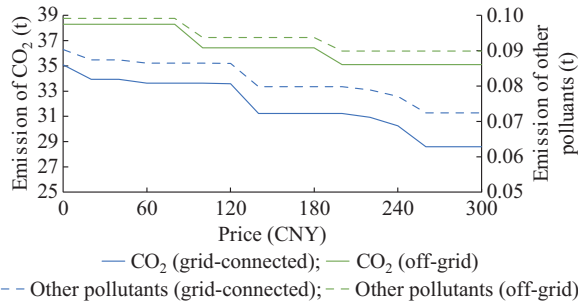


Fig. 10. Impact of carbon trading price on pollutant emissions.

Figure 10 shows the impact of changes in carbon tax on pollutant emissions. It can be seen that the emissions of pollutants slowly decrease with the increase of prices, and the grid-connected carbon pollutant emissions initially decline gently. When the price reaches 140 CNY/t and 260 CNY/t, the pollutant emissions fall rapidly, which are 11.6% and 19.9%, respectively, lower than the case without carbon emission charge. As seen in Fig. 10, the off-grid pollutant emissions are not significantly affected by the price. When the carbon emission tax is 100 CNY/t and 200 CNY/t, the carbon emissions decrease by 4.9% and 8.3% in the off-grid mode, respectively, and the effect of pollutant emission control in the pollutant trading market is far less than that of the control strategy in the grid-connected mode. It can be seen that the grid-connected type is more sensitive to the carbon trading price.

Figure 11 shows the impact of carbon trading prices on various energy consumption. It can be seen that as the price of carbon trading market increases, the system gradually

shifts from grid power supply mode to the consumption of natural gas, and more system output is generated by clean energy units. The purchase and sale of electricity have been reduced, and the off-grid type also consumes more electric power due to the lack of demand response and adjustment of ES equipment.

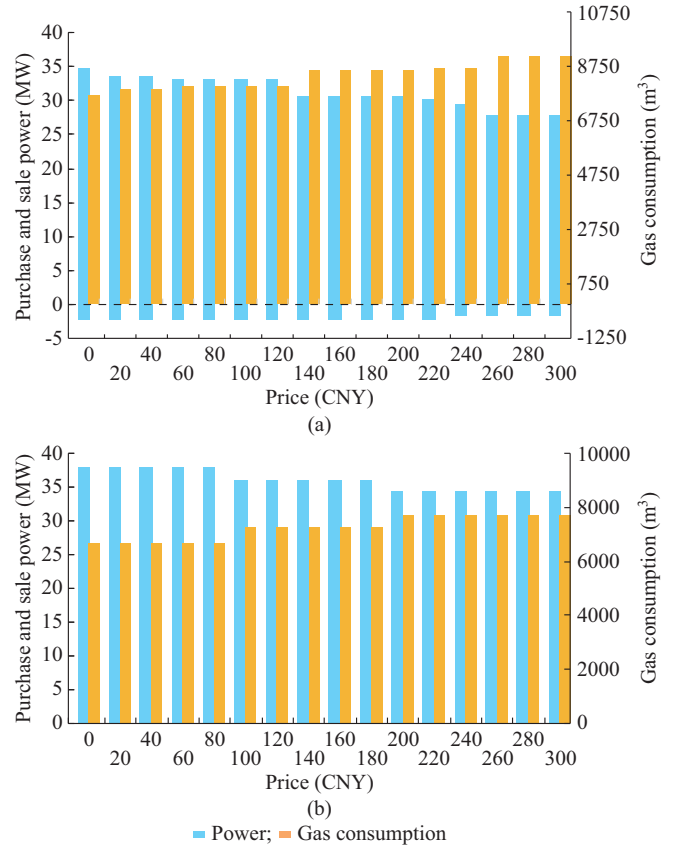


Fig. 11. Impact of carbon trading prices on energy consumption.

VI. CONCLUSION

Based on the concept of EH, this paper establishes an optimization model including storage and EVs considering emission trading in multi-energy system (MES). The analysis results show that the proposed optimization model and operation strategy can meet the desired comfortable temperature conditions of the user. The energy-consuming equipment participating in the demand response can reduce the grid pressure through load transfer multiple energy sources. They can complement each other to achieve the lowest total operation cost, and sell electricity to the grid when the energy supply is excessive, which significantly improves the economic benefits of system operation. The electricity during the period of valley electricity price and the heat energy recovered by the CCHP unit are stored to save energy. The optimization model considers the pollutant trading market constraint effectively to reduce the pollutant emissions of the district operation. The simulation results show that the district will use clean energy to generate electricity and reduce the use of electricity.

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Yanhong Luo received the B.S. degree in automation control, the M.S. degree and the Ph.D. degree in control theory and control engineering from Northeastern University, Shenyang, China, in 2003, 2006 and 2009, respectively. She is currently with Northeastern University as an Associate Professor. Her research interests include approximate dynamic programming, neural networks, adaptive control, fuzzy control, and their industrial application.

Xinwen Zhang received the B.S. degree from University of Shanghai for Science and Technology, Shanghai, China, in 2017. She is currently pursuing the M.S. degree with the College of Information Science and Engineering, Northeastern University, Shenyang, China. Her current research interests include integrated energy system and cooperative game theory.

Dongsheng Yang received the B.S., M.S. and Ph.D. degrees from Northeastern University, Shenyang, China, in 1999, 2004 and 2007, respectively. He is currently the deputy dean at Intelligent Electrical Science and Technology Institute, College of Information Science and Engineering, Northeastern University, Shenyang, China. His research interests include complex network theory, energy efficiency optimization control and intelligent allocate electricity technology.

Qiuye Sun received the B.S. degree in power system and its automaton from the Northeast Dianli University of China, Jilin City, China, in 2000, the M.S. degree in power electronics and drives, and the Ph.D. degree in control theory and control engineering from the Northeastern University, Shenyang, China, in 2004 and 2007, respectively. Since 2014, he has been a Full Professor with the School of Information Science and Engineering, Northeastern University, China. His main research interests are optimization analysis technology of power distribution network, network control of distributed generation system, microgrids, and Energy Internet.