

Economic dispatch of community-integrated energy system considering demand-side coordinated response

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Abstract. There are a large number of potential schedulable resources in the integrated energy system of electricity, heat, cold, and gas. However, most of these energy sources are currently operated separately, with low system flexibility, low energy utilization rate, and serious abandonment of wind and solar energy. In order to improve the flexibility of integrated energy systems and the capacity of renewable energy consumption, an economic dispatch of community-integrated energy systems considering demand-side coordinated response is proposed. Firstly, according to various energy characteristics, mathematical models of various energy forms are established, including wind energy, photovoltaic, gas turbine, gas boiler, and other component characteristics modeling. Secondly, an economic optimal scheduling model of community-integrated energy system considering demand side response is established, including the constraints and objective functions of the optimization model, and the optimization model is solved based on the Yalmip toolbox and Cplex solver in Matlab software. Finally, the effectiveness of the proposed strategy is verified by a simulation example.

Keywords: Integrated energy system, Demand-side coordinated response, Economic optimal scheduling model, Yalmip toolbox, Cplex solver.

1 Introduction

Electrical energy consumption is necessary for all areas of modern life, covering households, enterprises, construction, farming, teaching, medicine, research, and innovation [1]. The installed capacity of new energy sources such as wind turbines and photovoltaics is increasing year by year [2–4]. At the same time, industrial, commercial, and residential users need more and more forms of capacity, but most of these energy systems are currently operating separately [5]. The separate operation of power, heat, cold, and gas energy systems leads to low system flexibility, low energy utilization rate, and serious abandonment of wind and light. The combined scheduling of electric heating and cooling gas is a little obvious, which can effectively improve the operation efficiency of the whole system, reduce the waste of different energy sources, reduce the operation cost of the system, and improve the stability and flexibility of the system [6].

To balance social development and environmental protection, it is urgent to seek the optimization of energy structure and the efficient use of energy [7, 8]. In recent years, the integrated energy system has developed rapidly

[9]. Integrated Energy Systems (IES) refers to the coupling of electricity, gas, heat, cold, and other energy sources, which can effectively improve energy utilization efficiency and promote sustainable energy development while meeting the diversified energy use needs of the system. Compared with the traditional distributed energy system, the integrated energy system is a complex system that includes a variety of energy sources, such as electricity, gas, heat, etc. Specifically, the system contains a variety of different energy resource inputs, and has many different forms of output and transportation, is a regional energy interconnection system. It is not just a simple superposition of multiple resources, but at the system level, for the comprehensive complementary use of different energy sources, coordinate the mutual conversion between various energy sources, to achieve the most reasonable results and benefits [10]. The coordinated and sustainable development of multi-energy systems is the inevitable trend of the development of integrated energy systems in the future. Therefore, integrated energy systems have broad development prospects.

At present, the potential of integrated energy systems is increasing [11, 12]. In the aspect of IES model construction, according to the difference between load and equipment output, Power to Gas (P2G) technology and gas turbine technology are used to cut peak and fill valley in

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the literature [13], and the index of peak shaving and valley filling is introduced into the objective function, and the optimization is established. In reference [14], the multi-energy complementary strategy was used to increase the consumption of renewable energy. The IES system including the coupling of cogeneration units and electric heating equipment was studied, and the energy storage characteristics of the heating network were considered. Literature [15] established a multi-objective IES scheduling model and a real-time demand response model based on energy prices. Reference [16] pointed out that it is limited to relying solely on the energy storage system for regulation. Therefore, on this basis, a composition of electricity, heat, and hydrogen is proposed. In [17, 18], for multi-energy complementary systems, the minimum sum of energy purchase cost and operation and maintenance cost is taken as the objective function of the system, and the corresponding optimal scheduling model is established. Reference [19] constructed an integrated energy system of “cold-heat-electricity-gas”, and established an operation optimization model of regionally integrated energy systems with the objective function of net profit, energy utilization efficiency, and load matching of regionally integrated energy systems. In literature [20], a comprehensive energy system containing electric, hot, and cold systems was studied. At the same time, it is proposed that the flexible load in the integrated energy system participates in the optimal operation of the system. However, the modeling methods for flexible loads of electric, hot, and cold were single, and the differences in energy use characteristics between loads were not taken into account. Literature [21] puts forward energy management strategies to reduce IES operating costs, establishes flexible electrical and thermal load models, and divides electrical loads into two types: transferable load and reducible load.

Inspired by the aforementioned issues, this paper proposes an economic dispatch of community integrated energy system considering a demand-side coordinated response. Firstly, mathematical models of various energy forms are established according to various energy characteristics, including fan, photovoltaic, gas turbine, gas boiler, and other component characteristics modeling. Secondly, the multi-energy complementary optimization model including electricity, cold, and hot energy forms is established, and the load-side demand-side response is taken into account. Finally, Matlab software Yalmip toolbox and Cplex solution are used to solve the optimization model, and the concrete expression of energy Internet multi-energy complementarity is given.

2 Integrated energy system composition

The schematic diagram of the regional integrated energy system is shown in Figure 1, which mainly includes three energy subsystems: electricity, cold, and heat. Among them, the power grid, gas turbine, photovoltaic power supply, and gas boiler are the energy input of the integrated energy system; The electric boiler can convert electrical energy into thermal energy, the electric refrigerator can convert electrical energy into cold, and the absorption refrigerator is the liaison element of the cold and hot system, and the three

liaison elements realize the mutual conversion between various energy sources within the integrated energy system. The load types are generally divided into flexible load and rigid load. The flexible load can participate in the demand side response of the integrated energy system, while the rigid load cannot. The flexible load can be divided into translation load, reduction load, and transfer load.

3 Multi-energy complementary optimization operation scheduling model of regional integrated energy system

The multi-energy complementary pre-day optimization operation scheduling model of the regional integrated energy system, which includes electricity, cold and hot energy, is established to optimize the pre-day optimization operation of the integrated energy system according to the predicted output and load information of photovoltaic and other new energy sources, making the integrated energy system run economically. In the field of optimization, the optimal scheduling model belongs to the category of planning problems. A complete optimization model includes the constraints of the optimization model, the objective function of the optimization model, and the decision variables of the optimization model, which will be analyzed in detail later. Constraints of multi-energy complementary optimization operation model of regionally integrated energy system containing electric, cold, and hot energy.

3.1 Constraint conditions of multi-energy complementary optimization operation model for regional integrated energy system

1. Power grid purchase and sale capacity constraints

The integrated energy system cannot purchase or sell electricity to the power system in excess of the maximum allowable power value of the line, that is

$$\begin{cases} 0 \leq P_{\text{pur}}(t) \leq P_{\text{link.max}} \cdot \alpha_{\text{pur}}(t) \\ 0 \leq P_{\text{sell}}(t) \leq P_{\text{link.max}} \cdot \alpha_{\text{sell}}(t) \end{cases} \quad (1)$$

where $P_{\text{link.max}}$ is the maximum running power of the line; $\alpha_{\text{pur}}(t)$, $\alpha_{\text{sell}}(t)$ indicates the status of power purchase and sale; $P_{\text{sur}}(t)$ is the power purchased from the grid; $P_{\text{sell}}(t)$ is the amount of power sold to the grid.

2. Constraints on the output capacity of photovoltaic and wind-distributed power supplies

The maximum active power output of the photovoltaic power supply cannot exceed the capacity of the photovoltaic power supply, that is

$$0 \leq P_{\text{pv}}(t) \leq S_{\text{pv}} \quad (2)$$

$$0 \leq P_{\text{wind}}(t) \leq S_{\text{wind}} \quad (3)$$

where P_{pv} is photovoltaic active power output; P_{wind} is wind active power output; S_{pv} is the capacity of

The constraint on the maximum up and down climb rates is

$$-r_{EB,down}\Delta t \leq Q_{i+1}^{EB} \cdot Q_i^{EB} \leq r_{EB,up}\Delta t \quad (13)$$

where $r_{EB,up}$ and $r_{EB,down}$ indicate the maximum climbing speed of the electric boiler.

7. Operation constraint of electric refrigerator

The output cold power of the electric refrigerator cannot exceed the maximum output power of the electric refrigeration

$$0 \leq C_i^{EC} \leq C_{max}^{EC} \quad (14)$$

where C_{max}^{EC} is the maximum output power of the electric refrigerator; C_i^{EC} is the output power of the electric refrigerator.

The constraint on the maximum up and down climb rates is

$$-r_{EC,down}\Delta t \leq C_{i+1}^{EC} - C_i^{EC} \leq r_{EC,up}\Delta t \quad (15)$$

where $r_{EC,up}$ and $r_{EC,down}$ indicate the maximum climbing rates of the electric refrigerator.

8. Operating constraints of absorption chillers

Absorption chillers supply the cold load of the integrated energy system, and the output cold power should be within the limit value, that is

$$0 \leq C_i^{AC} \leq C_{max}^{AC} \quad (16)$$

where C_{max}^{AC} is the maximum output power of the absorption refrigerator; C_i^{AC} is the output power of the absorption refrigerator.

The output power of the absorption refrigerator is also affected by the climbing speed, that is

$$-r_{AC,down}\Delta t \leq C_{i+1}^{AC} - C_i^{AC} \leq r_{AC,up}\Delta t \quad (17)$$

where $r_{AC,up}$ is the maximum ascending climbing speed of the absorption refrigerator; $r_{AC,down}$ is the maximum downward climbing speed of the absorption refrigerator.

9. Constraints on the operation of the energy storage device

Take the battery as an example. Overcharging and over-discharging of the battery will affect the operating state of the battery. Therefore, the limit of the charged state of the battery must be within the safe and reliable range, that is

$$S_{BAT,min} \leq S_i^{BAT} \leq S_{BAT,max} \quad (18)$$

where $S_{BAT,max}$ and $S_{BAT,min}$ are the safe upper and lower limits of the battery charging state.

A battery can work in only one state at a time

$$X_i^{cha} \cdot X_i^{dis} = 0 \quad (19)$$

where X_i^{cha} , X_i^{dis} the variable 0–1, 1 indicates the on state, 0 indicates the off state.

When the battery participates in the optimization operation of the integrated energy system, the state of charge needs to be equal at the beginning and end of the dispatching cycle, that is

$$S_0^{BAT} = S_T^{BAT} \quad (20)$$

where S_0^{BAT} is the charged state of the battery at the beginning of the scheduling cycle when the battery participates in the optimization operation of the integrated energy system.

To ensure the working lifetime of the battery and improve the overall operation economy and reliability of the comprehensive energy system, the battery cannot be charged and discharged too much.

$$\begin{cases} 0 \leq P_i^{cha} \leq 0.2E_{BAT}X_i^{cha} \\ 0 \leq P_i^{dis} \leq 0.2E_{BAT}X_i^{dis} \end{cases} \quad (21)$$

where E_{BAT} indicates the rated capacity of the battery; P_i^{cha} is the charging power of the battery in the i period; P_i^{dis} is the discharge power of the battery in the i period; X_i^{cha} is the variable 0–1, indicating whether the battery is in the charging state. 1 indicates that the battery is in the charging state, and 0 indicates that the battery is in the non-charging state. X_i^{dis} is the variable 0–1, indicating whether the battery is in the discharge state. 1 indicates that the battery is in the discharge state, and 0 indicates that the battery is not in the discharge state.

Similarly, the charge and discharge times of the battery will affect the operating lifetime of the battery, and then affect the overall equipment investment cost of the comprehensive energy system, so it is necessary to control the charge and discharge times of the energy storage equipment to ensure the working time of the energy storage equipment.

$$\begin{cases} \frac{1}{2} \sum_{t=1}^T |X_{t+1}^{cha} - X_t^{cha}| \leq N_1^{BAT} \\ \frac{1}{2} \sum_{t=1}^T |X_{t+1}^{dis} - X_t^{dis}| \leq N_2^{BAT} \end{cases} \quad (22)$$

where N_1^{BAT} is the safe charging times of energy storage equipment; N_2^{BAT} is the safe discharge times of the energy storage device.

10. Translational load constraint

Translation load is a kind of flexible load, which can be translated into the whole section to relieve the load pressure of the integrated energy system in a certain period of time. Taking translatable load L_{shift} as an example, L_{shift} can be represented by a set of vectors with a certain continuity, where t_s is the initial time of the translatable load and t_D is the continuous time of the translatable load.

$$L_{shift} = [0, \dots, P_{t_s}^{shift}, P_{t_s+1}^{shift}, \dots, P_{t_s+t_D-1}^{shift}, \dots, 0] \quad (23)$$

It is assumed that the time interval to which the shiftable load can be shifted is $[t_{sh-}, t_{sh-}+1, \dots, t_{sh+}]$. Considering that the shiftable load needs to be shifted as a whole, the initial value of the shiftable time interval must be satisfied.

If it is not satisfied, some of the shiftable load will exceed the shiftable time interval.

$$S_{\text{shift}} = \{[t_{\text{sh}-}, t_{\text{sh}-} + 1, \dots, t_{\text{sh}+} - t_D + 1], t_s\} \quad (24)$$

Whether load translation is carried out at the initial value can be expressed by the vector X_i^{shift} , $X_i^{\text{shift}} = 1$ indicates that load translation is carried out at this initial value, and $X_i^{\text{shift}} = 0$ indicates that no load translation is carried out at this initial value.

$$\left\{ [X_{t_{\text{sh}-}}^{\text{shift}}, X_{t_{\text{sh}-}+1}^{\text{shift}}, \dots, X_{t_{\text{sh}+}-t_D+1}^{\text{shift}}], X_{t_s}^{\text{shift}} \right\} \quad (25)$$

where $X_i^{\text{shift}} = 1$ indicates the shift load in period i ; $X_i^{\text{shift}} = 0$ indicates no shift load in period i .

In order to facilitate the integrated energy system scheduling, the shiftable load generally carries out only one shift, so X_i^{shift} should meet the constraint.

$$\sum_{i \in S_{\text{shift}}} X_i^{\text{shift}} = 1 \quad (26)$$

11. Transferable load constraint

Transferable load means that the load of a certain period can be transferred to another period, to achieve the purpose of peak cutting and valley filling. Taking transferable load L_{tran} as an example, X^{tran} indicates whether load transfer is performed in the corresponding period, $X_i^{\text{tran}} = 1$ indicates that load transfer is performed in the period, and $X_i^{\text{tran}} = 0$ indicates that load transfer is not performed in the period.

$$X^{\text{tran}} = [X_1^{\text{tran}}, X_2^{\text{tran}}, \dots, X_T^{\text{tran}}] \quad (27)$$

At the same time, the transfer power will have certain constraints, and the transfer load cannot be completely transferred, so as not to affect the daily life of users in the park, so the constraints should be met

$$X_i^{\text{tran}} P_{\min}^{\text{tran}} \leq P_i^{\text{tran}} \leq X_i^{\text{tran}} P_{\max}^{\text{tran}} \quad (28)$$

where $P_{\max}^{\text{tran}}$ is the transferable maximum; $P_{\min}^{\text{tran}}$ is a transferable minimum.

If the duration of the transferable load is not limited, the frequency of switching of electrical equipment in the park will be frequent, and the operating life of the user's electrical equipment will be affected. In this regard, it is necessary to limit the minimum duration of the transferable load, that is

$$\sum_{i=t}^{t+T_{\min}^{\text{tran}}-1} X_i^{\text{tran}} \geq T_{\min}^{\text{tran}} (X_t^{\text{tran}} - X_{t-1}^{\text{tran}}) \quad (29)$$

Since the transferable load operation only transfers the load but does not reduce the load, the total load before and after the load transfer will not change

$$\sum_{i=1}^T X_i^{\text{tran}} P_i^{\text{tran}} = P_{\text{sum}}^{\text{tran}} \quad (30)$$

where $P_{\text{sum}}^{\text{tran}}$ is the total power before the transferable load is transferred.

12. Reducible load constraints

The reducible load refers to the direct cutting operation of the load to ensure the balance of supply and demand of the integrated energy system. Take L_{cut} as an example

$$L_{\text{cut}} = [P_1^{\text{cut}}, P_2^{\text{cut}}, \dots, P_T^{\text{cut}}] \quad (31)$$

X^{cut} indicates whether the load is reduced in the corresponding period, $X_i^{\text{cut}} = 1$ indicates that the load is reduced in the period, and $X_i^{\text{cut}} = 0$ indicates that the load is not reduced in the period.

$$X_{\text{cut}} = [X_1^{\text{cut}}, X_2^{\text{cut}}, \dots, X_T^{\text{cut}}] \quad (32)$$

Load reduction will affect the comfort of users, taking the indoor building as an example, the reduction of cooling load will lead to excessive indoor temperature in summer; reducing the heat load will cause the indoor temperature to be too low in winter, which will lead to a poor user experience. Therefore, it is necessary to set the minimum duration of load shedding, the maximum duration of load shedding, and the upper limit of the number of load shedding.

$$\sum_{i=t}^{t+T_{\min}^{\text{cut}}-1} X_i^{\text{cut}} \geq T_{\min}^{\text{cut}} (X_t^{\text{cut}} - X_{t-1}^{\text{cut}}) \quad (33)$$

$$\sum_{i=t}^{t+T_{\max}^{\text{cut}}} (1 - X_i^{\text{cut}}) \geq 1 \quad (34)$$

$$\sum_{i=1}^T X_i^{\text{cut}} \leq N_{\max}^{\text{cut}} \quad (35)$$

13. Power balance constraint of integrated energy system

Power balance constraints mainly include electric power balance, thermal power balance, and cold power balance. The electric power balance of the integrated energy system is shown in equation (36)

$$\begin{aligned} & (P_i^{\text{pur}} - P_i^{\text{sell}}) + P_i^{\text{wind}} + P_i^{\text{pv}} + P_i^{\text{GT}} + P_i^{\text{FC}} + (P_i^{\text{dis}} - P_i^{\text{cha}}) \\ & = P_i^{\text{EB}} + P_i^{\text{EC}} + P_i^{\text{base}} + P_i^{\text{shift}} + P_i^{\text{tran}} + P_i^{\text{cut}}, \end{aligned} \quad (36)$$

$i = 1, 2, \dots, T$

The thermal power balance of the integrated energy system is shown as follows

$$\begin{aligned} & Q_i^{\text{GT}} + Q_i^{\text{EB}} + Q_i^{\text{GB}} + (Q_i^{\text{dis}} - Q_i^{\text{cha}}) - Q_i^{\text{AC}} \\ & = Q_i^{\text{base}} + Q_i^{\text{shift}} + Q_i^{\text{cut}}, \end{aligned} \quad (37)$$

$i = 1, 2, \dots, T$

where Q_i^{base} is the rigid heat load; Q_i^{shift} is the transferable heat load; Q_i^{cut} is reducible the heat load.

The cold power balance of the integrated energy system is shown as follows

Table 1. The constraints of the multi-energy complementary optimization operation model.

Constraints	Constraint type
1	Power grid purchase and sale capacity constraints equation (1)
2	Constraints on the output capacity of photovoltaic and wind-distributed power supplies equations (2) and (3)
3	Gas turbine operating constraints equations (4)–(7)
4	Fuel cell operating constraints equations (8) and (9)
5	Gas boiler operation constraints equations (10) and (11)
6	Electric boiler operation constraints equations (12) and (13)
7	Operation constraint of electric refrigerator equations (14) and (15)
8	Operating constraints of absorption chillers equations (16) and (17)
9	Constraints on the operation of the energy storage device equations (18)–(22)
10	Translational load constraint equations (23)–(26)
11	Transferable load constraint equations (27)–(30)
12	Reducible load constraints equations (31)–(35)
13	Power balance constraint of integrated energy system equations (36)–(38)

$$C_i^{AC} + C_i^{EC} + (C_i^{dis} - C_i^{cha}) - C_i^{base} = C_i^{shift} + C_i^{cut}, \quad (38)$$

$$i = 1, 2, \dots, T$$

where C_i^{base} is the rigid cooling load; C_i^{shift} is the transferable cooling load; C_i^{cut} is reducible the cooling load.

The constraints of the multi-energy complementary optimization operation model of the integrated energy system are shown in Table 1.

3.2 Objective function of multi-energy complementary optimization operation model for regional integrated energy system

The multi-energy complementary optimization operation model of a regional integrated energy system containing electricity, cold, hot, and other energy sources aims at system cost. The daily cost of an integrated energy system includes system power purchase cost, distributed power supply operation cost, etc., so the objective function is

$$\begin{aligned} \min F = & F_{grid} + F_{DG} + F_{BAT} + F_{FC} + F_{EB} + F_{GT} + F_{GB} \\ & + F_{TS} + F_{AC} + F_{EC} + F_{CS} + F_{shift}^e + F_{tran}^e + F_{cut}^e \\ & + F_{shift}^t + F_{cut}^t + F_{shift}^c + F_{cut}^c \end{aligned} \quad (39)$$

1. Power purchase costs for integrated energy systems

The integrated energy system needs to buy electricity from the grid when it lacks power, and the integrated energy system can sell electricity to the grid when it has sufficient power, so the cost of unified power purchase of the integrated energy system within a dispatching cycle is related to the purchase and sale of electricity.

$$\begin{cases} F_{pur} = \sum_{i=1}^T K_{pur,i}^e P_i^{pur} \\ F_{sell} = \sum_{i=1}^T K_{sell,i}^e P_i^{sell} \end{cases} \quad (40)$$

where $K_{pur,i}^e$ is the purchase price from the power grid for the integrated energy system; $K_{sell,i}^e$ is the price of electricity sold to the grid for the integrated energy system.

Therefore, the purchase cost of the integrated energy system is

$$F_{grid} = F_{pur} - F_{sell} \quad (41)$$

2. Photovoltaic, wind power supply operating costs

The distributed power supply in the integrated energy system is generally composed of photovoltaic, wind, and other new energy sources. In this paper, only photovoltaic and wind power are considered in the integrated energy system, and the total operation cost of photovoltaic and wind-distributed power supply within a scheduling cycle is

$$F_{DG} = \sum_{i=1}^T K_{wind} P_i^{wind} + \sum_{i=1}^T K_{pv} P_i^{pv} \quad (42)$$

where K_{wind} is the kilowatt-hour cost of wind-distributed power supply; K_{pv} is the kilowatt-hour cost of photovoltaic distributed power supply.

3. Operating cost of gas equipment

The operating cost of gas equipment (gas turbine, gas boiler, and fuel cell) in one dispatching cycle is shown in the equation

$$\begin{cases} F_{GT} = \sum_{i=1}^T K_{gas} V_i^{GT} + \sum_{i=1}^T K_{GT} P_i^{GT} \\ F_{GB} = \sum_{i=1}^T K_{gas} V_i^{GB} + \sum_{i=1}^T K_{GB} P_i^{GB} \\ F_{FC} = \sum_{i=1}^T K_{gas} V_i^{FC} + \sum_{i=1}^T K_{FC} P_i^{FC} \end{cases} \quad (43)$$

where V_i^{GT} is the natural gas consumption of the gas turbine; K_{GT} is the KWH cost of the gas turbine; V_i^{GB} is the natural gas consumption of gas-fired boilers; K_{GB} is the kilowatt-hour cost of the gas-fired boiler; V_i^{FC} is the fuel

Table 2. The objective functions of the multi-energy complementary optimization operation model.

Objective functions	Objective functions type
1	Total cost equation (39)
2	Power purchase costs for integrated energy systems equations (40) and (41)
3	Photovoltaic, wind power supply operating costs equation (42)
4	Operating cost of gas equipment equation (43)
5	Operating costs of electric boilers, electric chillers, and absorption chillers equation (44)
6	The operating cost of energy storage equipment equation (45)
7	Shifting load compensation costs equation (46)
8	Transferable load compensation costs equation (47)
9	Reducible load compensation costs equation (48)

cell gas consumption; K_{FC} is the kilowatt-hour cost of the fuel cell; K_{gas} is the cost of natural gas.

4. Operating costs of electric boilers, electric chillers, and absorption chillers

The operating costs of the electric boiler, electric chiller, and absorption chiller in one dispatching cycle are respectively

$$\begin{cases} F_{EB} = \sum_{i=1}^T K_{EB} Q_i^{EB} \\ F_{EC} = \sum_{i=1}^T K_{EC} C_i^{EC} \\ F_{AC} = \sum_{i=1}^T K_{AC} C_i^{AC} \end{cases} \quad (44)$$

where K_{EB} is the operating cost factor of the electric boiler; K_{EC} is the operating cost factor of the electric refrigerator; K_{AC} is the operating cost factor of the absorption refrigerating machine.

5. The operating cost of energy storage equipment

Within a scheduling cycle, the operating cost of energy storage equipment (battery, heat storage tank, cold storage tank) is shown in the formula

$$\begin{cases} F_{BAT} = \sum_{i=1}^T K_{cha} P_i^{cha} X_i^{cha} + \sum_{i=1}^T K_{dis} P_i^{dis} X_i^{dis} \\ F_{TS} = \sum_{i=1}^T K_{cha^*} Q_i^{cha} Y_i^{cha} + \sum_{i=1}^T K_{dis^*} Q_i^{dis} Y_i^{dis} \\ F_{CS} = \sum_{i=1}^T \tilde{K}_{cha} C_i^{cha} R_i^{cha} + \sum_{i=1}^T \tilde{K}_{dis} C_i^{dis} R_i^{dis} \end{cases} \quad (45)$$

where K_{cha} is the cost coefficient of energy storage equipment; K_{dis} is the discharge cost coefficient of the energy storage device. K_{cha^*} is the cost coefficient of a heat storage tank; K_{dis^*} is the cost coefficient of heat release in a heat storage tank; $\tilde{K}_{cha}$ is the cost coefficient of filling a cold storage tank; $\tilde{K}_{dis}$ is the cost coefficient of a cooling storage tank.

6. Shifting load compensation costs

The compensation costs of movable load (movable electrical load, movable thermal load, and movable cold load) are respectively

$$\begin{cases} F_{shift}^e = F_{cost}^{shift} \cdot P_{sum}^{shift} \cdot \sum_{i=t_{sh-}}^{t_{sh+}-t_D+1} X_i^{shift} \\ F_{shift}^t = F_{cost^*}^{shift} \cdot Q_{sum}^{shift} \cdot \sum_{i=t_{sh^*}-}^{t_{sh^*}+ -t_D^*+1} Y_i^{shift} \\ F_{shift}^c = \tilde{F}_{cost}^{shift} \cdot C_{sum}^{shift} \cdot \sum_{i=\tilde{t}_{sh-}}^{\tilde{t}_{sh+}-\tilde{t}_D+1} R_i^{shift} \end{cases} \quad (46)$$

where F_{cost}^{shift} is the cost coefficient of translatable load; P_{sum}^{shift} is the total transferable electrical load; $F_{cost^*}^{shift}$ is the cost coefficient of transferable heat load, and Q_{sum}^{shift} is the total transferable heat load. $\tilde{F}_{cost}^{shift}$ is the cost coefficient of the translational cooling load, and C_{sum}^{shift} is the total translational cooling load.

7. Transferable load compensation costs

$$F_{tran}^e = F_{cost}^{tran} \cdot \sum_{i \in h} X_i^{tran} P_i^{tran} \quad (47)$$

where F_{cost}^{tran} is the cost coefficient of transferable load. Reducible load compensation costs The compensation cost of the reduced load (the reducible electric load, the reducible heat load, and the reducible cold load) is

$$\begin{cases} F_{cut}^e = F_{cost}^{cut} \sum_{i=1}^T \theta_i X_i^{cut} P_i^{cut} \\ F_{cut}^t = F_{cost^*}^{cut} \sum_{i=1}^T \theta_{*i} Y_i^{cut} Q_i^{cut} \\ F_{cut}^c = \tilde{F}_{cost}^{cut} \sum_{i=1}^T \tilde{\theta}_i R_i^{cut} C_i^{cut} \end{cases} \quad (48)$$

where F_{cost}^{cut} is the cost coefficient of electric load that can be reduced; $F_{cost^*}^{cut}$ can reduce the cost factor of heat load; $\tilde{F}_{cost}^{cut}$ indicates that the cooling load cost factor can be reduced. The objective functions of the multi-energy complementary optimization operation model for a regional integrated energy system are shown in Table 2.

3.3 Regional integrated energy system multi-energy complementary day optimization operation scheduling model to solve the overall process

The optimal operation scheduling model of a regional integrated energy system with electric, cold, and hot energy

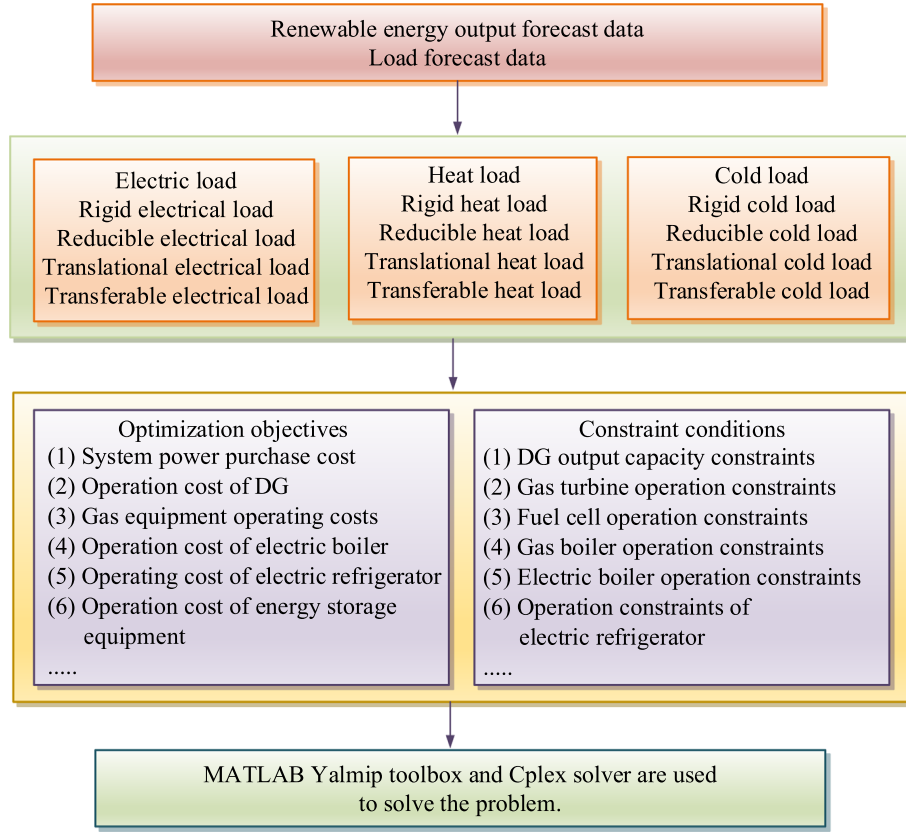


Fig. 2. The solution process of the optimal operation scheduling model.

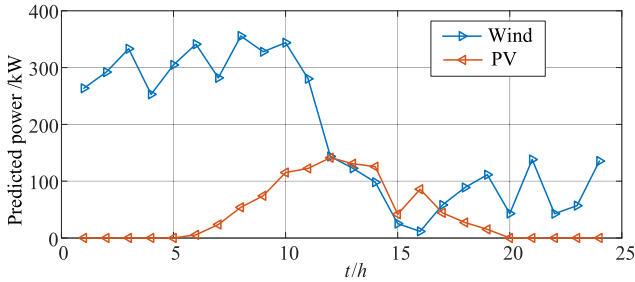


Fig. 3. The forecast data of wind and PV output power.

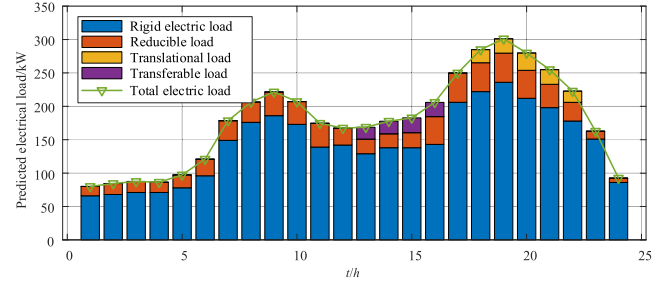


Fig. 4. Predicted electrical load.

includes multiple energy forms and energy conversion, with many decision variables and large solution space. According to the day-before forecast data of wind turbine output and load power, the controllable variables in the controllable components and flexible loads are taken as the decision variables, and the operation limitations of the controllable components, the supply and demand power balance in the system and the inherent limitations of the controllable load are taken as the constraint conditions, and the daily operating cost of the system is minimized as the optimization objective. Among them, the constraints of the optimization model have been introduced in detail in Section 3.2. The objective function of the optimization model has been introduced in detail in Section 3.1 of the paper. The proposed

optimization model is a mixed integer programming model, in this regard, this paper uses the Yalmip toolbox and Cplex solver to solve the problem based on Matlab software, and the solution process is shown in Figure 2.

4 Case study

The forecast data of wind and PV output power are shown in Figure 3, and the time scale is set to 1 h.

The forecast data for electrical load, thermal load, and cooling load are shown in Figures 4–6, and the time scale is 1 h.

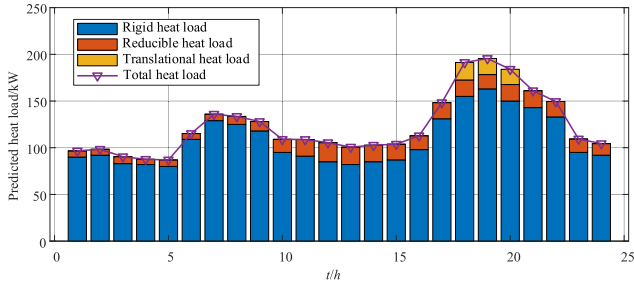


Fig. 5. Predicted heat load.

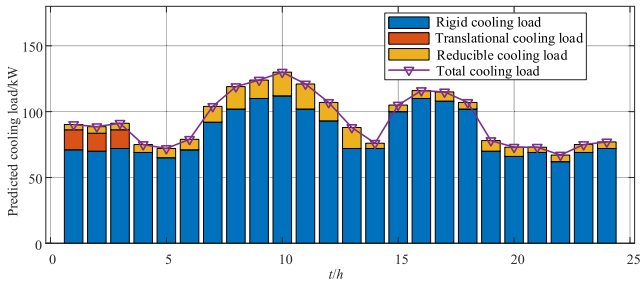


Fig. 6. Predicted cooling load.

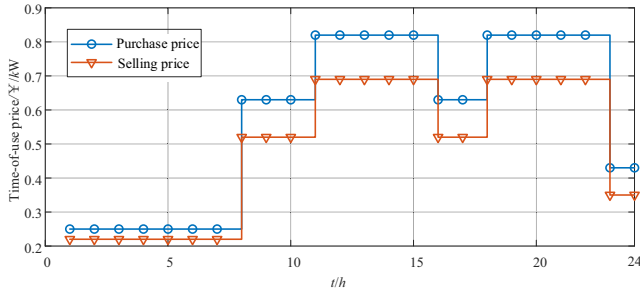


Fig. 7. Time of use price.

The price of natural gas is 3.23 ¥/m³, the calorific value of combustion is 9.78 km/m³, and the TOU price is shown in Figure 7.

The interactive power with the power grid, wind power output, photovoltaic output, fuel cell output, gas turbine, and battery output is shown in Figure 8. It can be seen that the integrated energy system realizes the consumption of new energy and promotes the construction of a new power system through a variety of multi-energy complementary coordination and optimization.

The output thermal power of the gas boiler, gas turbine, electric boiler, and heat storage tank is shown in Figure 9.

The output of the absorption refrigerator, electric refrigerator, and cold storage tank is shown in Figure 10.

Taking electrical load as an example, the changes in electrical load that can be shifted, transferred, reduced, and total electrical load are shown in Figures 11–14. It can be seen that by participating in the demand side

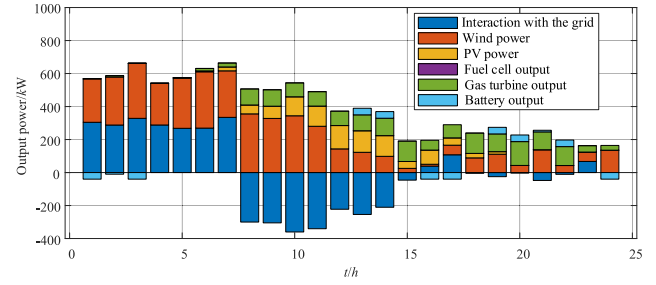


Fig. 8. Supply power to load each equipment output.

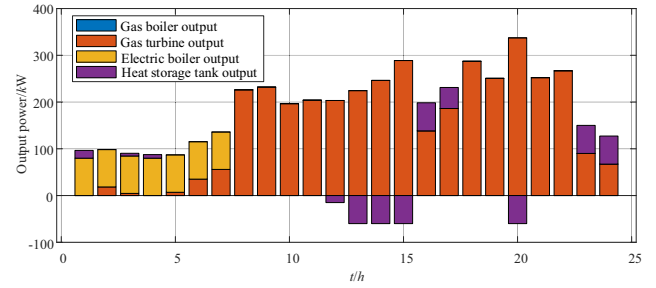


Fig. 9. The output thermal power of gas boiler, gas turbine, electric boiler, and heat storage tank.

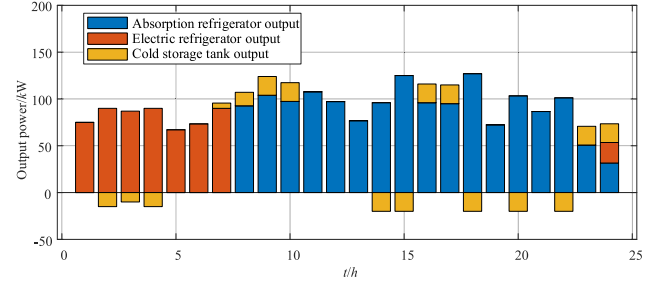


Fig. 10. The output of absorption refrigerator, electric refrigerator, and cold storage tank.

response of the integrated energy system with a flexible load, the purpose of peak cutting and valley filling is achieved.

5 Conclusion

In order to improve the flexibility of integrated energy systems and the capacity of renewable energy consumption, an economic dispatch of community-integrated energy systems considering demand-side coordinated response is proposed. Relevant conclusions are as follows:

1. Mathematical models of various energy forms are established according to various energy characteristics, including wind, photovoltaic, gas turbine, gas boiler, and other component characteristics modeling.

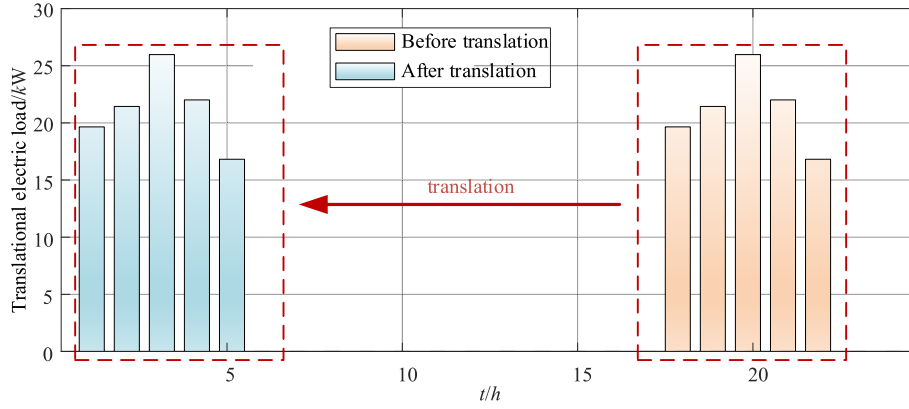


Fig. 11. Translational electric load.

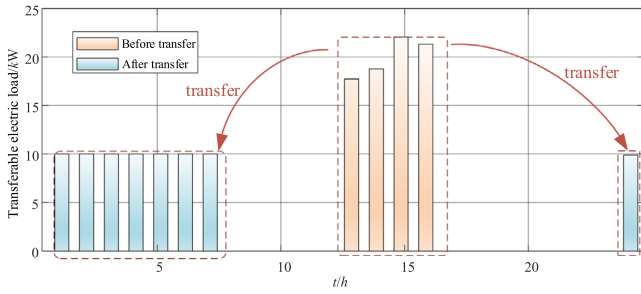


Fig. 12. Transferable electric load.

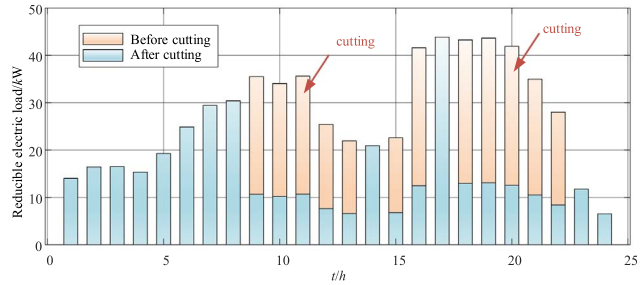


Fig. 13. Reducible electric load.

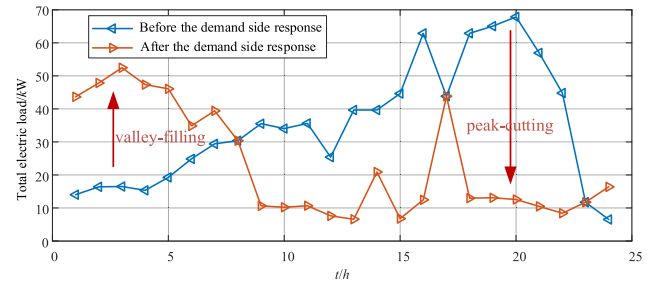


Fig. 14. Total electric load.

2. The multi-energy complementary optimization model including electricity, cold, and hot energy forms is established, and the load-side demand-side response is taken into account.
3. Through simulation results, it can be seen that by participating in the demand side response of the integrated energy system with flexible load, the purpose of peak cutting and valley filling is achieved.

At the same time, there are still some defects or limitations, which need to be further studied in the follow-up work, as follows:

1. The flexible load participates in the demand side response of the integrated energy system, and the influence of the change of the flexible load on the

user's electricity comfort in the integrated energy system is not considered, which needs further study.

2. There is still a certain gap between the optimization mathematical model proposed in this paper and the actual operation of the integrated energy system. At present, it is only a theoretical analysis and has not yet completed the follow-up landing.
3. The optimization mathematical model proposed in this paper is based on the accurate prediction of new energy power generation and load of integrated energy system, but there is still a gap with the actual operation, and the inaccuracy of prediction needs to be further considered in the follow-up.

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