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OPTIMAL SCHEDULING OF INTEGRATED ENERGY SYSTEMS BASED ON MIXED INTEGER LINEAR PROGRAMMING WITH FLEXIBLE LOAD ACCOUNTING

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Integrated energy systems can achieve optimal use of resources and improve the utilization rate of integrated energy resources, which is an important initiative to achieve energy saving and emission reduction. Taking into account the effects of different integrated energy equipment, electricity purchase prices, and natural gas prices, a mixed integer linear model for the optimal allocation and dispatching operation of integrated energy systems is established, and the dispatching operation of integrated energy systems on different typical days, taking into account the flexible load of electricity, is explored. The results show that the system tends to allocate more electrical equipment and reduce the capacity of heating and cooling equipment, while the total cost of allocation is reduced when the flexible load is taken into account. The deployment of flexible loads reduces dispatch costs, mainly in terms of annual investment costs, annual operating costs, and annual environmental costs.

Keywords: flexible loads, integrated energy systems, optimal allocation, optimal dispatch

1. Introduction

With the increasing national emphasis on improving multi-energy supply, increasing the proportion of renewable energy [1], and improving integrated energy efficiency [2-4], integrated energy systems (IES) with multi-functional synergies have become one of the important directions for new energy systems [5-7]. However, as an emerging project, integrated energy systems have a large amount of energy coupling within them [8-9]. The capacity ratios and dispatching situations between different forms of energy devices are complicated due to various factors such as feed-in tariffs and natural gas prices [10], and there are still

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many problems in the practical application [11]. In addition, with the attention of all walks of life to the comprehensive energy system, the complexity and variety of load forms also pose further challenges to the research of the comprehensive energy system. Meanwhile there are few existing studies on the impact of electricity purchase prices and natural gas prices on the allocation of integrated energy systems, and few studies have analyzed the impact of different integrated energy equipment on optimal allocation. Therefore, in view of the above problems, it is necessary to carry out in-depth research on the dispatching operation of integrated energy system and explore the dispatching operation problems in different scenarios.

Flexible load is a kind of load that can actively participate in the two-way interaction of power grid. In the integrated energy system, increasing flexible load can flexibly and variably participate in the operation control of power grid, thus reducing resource consumption and operation cost and improving the utilization rate of comprehensive energy. Therefore, this paper introduces flexible load and mixed integer linear programming model to analyze the influence of flexible load configuration on the dispatching cost of integrated energy system, and analyzes the dispatching operation of each equipment and flexible load in different typical days under the optimal configuration.

In the actual scheduling operation of integrated energy systems, taking into account flexible loads can optimize load profiles, promote renewable energy consumption and reduce new installed capacity [12-13]. Studies were conducted for the optimal dispatching problem of integrated energy systems containing flexible loads [14-15], Bei Dong et al. (2018) and Chen Jiming et al. (2022) developed an analysis of the day-ahead dispatching problem of flexible loads [16-17], Dongmei Zhao et al. (2019) and Shengchun Yang et al. (2014) did a modeling study on the multi-scale dispatching problem of flexible loads [18-19], and Jiang Yuechun et al. (2019) proposed integrated energy to optimal scheduling method that takes into account human comfort and flexible loads [20].

In summary, existing integrated energy dispatching problems mainly study system day-ahead dispatching and short-term multi-scale dispatching. Few studies have analyzed the dispatching operation problems under different typical days, while less research has been conducted on the participation of flexible loads in dispatching. Therefore, the innovation of this paper lies in the comprehensive comparation of unit output and flexible load dispatching under different typical days, the dispatching priorities under different conditions with the economy as the premise are analyzed, the scheduling of flexible load and integrated energy unit equipment for the optimal scheme are optimized.

2. Flexible load modeling

A flexible load is a load that can actively participate in the two-way interaction of the grid. In an integrated energy system, the addition of a flexible load allows for flexible and variable participation in the operational control of the grid, thereby reducing resource consumption, operating costs, improving integrated energy utilization. Flexible loads mainly include shiftable loads, transferable loads, and reducible loads.

(1) Shiftable loads

$$P_{t,k}^{shift} = u_{t,k}^{shift} L_k^{shift} \tag{1}$$

$$\sum_{t=\tau}^{\tau+ts_k^{shift}-1} u_{t,k} = ts_k^{shift}, \quad \tau \in \left[t_{k,sh-}^{shift}, t_{k,sh+}^{shift} - ts_k^{shift} + 1\right] \tag{2}$$

where ts_k^{shift} is the duration of the kth shiftable load, $u_{t,k}^{shift}$ denotes whether the kth shiftable load is dispatched to the 0-1 variable at time t, $ts_{k,sh+}^{shift}$ and $ts_{k,sh-}^{shift}$ are the upper and lower limits of the dispatched shift interval for the kth shiftable load, respectively, and L_k^{shift} and $P_{t,k}^{shift}$ are the rated power of the kth shiftable load and the power at time t after dispatch.

$$C_{shift} = C_p^{shift} \sum_k \sum_t P_{t,k}^{shift} \tag{3}$$

where C_{shift} and C_p^{shift} are the total compensation cost and the unit compensation cost of the shiftable load, respectively.

(2) Transferable loads

The transferable load shall be such that the total power before and after the transfer is equal, as follows.

$$\sum_{t=1}^{T} (L_{t,k}^{trans} - P_{t,k}^{trans}) = 0 \tag{4}$$

where $L_{t,k}^{trans}$ and $P_{t,k}^{trans}$ are the dispatch power and post-dispatch power of the kth transferable load at time t.

In addition, the transferable load divert shall be subject to a power range constraint and a minimum duration constraint, as follows.

$$u_{t,k}^{trans} P_{\min}^{trans} \le P_{t,k}^{trans} \le u_{t,k}^{trans} P_{\max}^{trans} \tag{5}$$

$$ts_{k,\min}^{trans} (u_{t,k}^{trans} - u_{t-1,k}^{trans}) \le \sum_{t=\tau}^{t+ts_{k,\min}^{trans}-1} u_{t,k}^{trans}, t \in \left[t_{k,tr-}^{trans}, t_{k,tr+}^{trans} - ts_{k,\min}^{trans} + 1\right] \tag{6}$$

where $u_{t,k}^{trans}$ is the 0-1 variable of whether the kth transferable load is dispatched to time t, $P_{\min}^{trans}$ and $P_{\max}^{trans}$ are the minimum and maximum dispatch power of the transferable load, $ts_{k,\min}^{trans}$ is the minimum runtime of the kth transferable load, and $t_{k,tr+}^{trans}$ and $t_{k,tr-}^{trans}$ are the upper and lower limits of the dispatch transfer interval of the kth transferable load, respectively.

$$C_{trans} = C_p^{trans} \sum_k \sum_t P_{t,k}^{trans} \tag{7}$$

where C_{trans} and C_p^{trans} are the total compensation cost and the unit compensation cost of the transferable load.

(3) Reducible loads

Reducible loads are loading whose power can be partially reduced, as follows.

$$P_t^{cut} = (1 - u_t^{cut} \alpha^{cut}) L_t^{cut} \tag{8}$$

where P_t^{cut} is the power at time t of the reducible load after reduction, u_t^{cut} is the 0-1 variable of whether the reducible load is reduced at time t, α^{cut} is the load reduction factor, and L_t^{cut} is the pre-reduction power of the transferable load at time t.

In addition, the reducible load needs to satisfy a minimum reducible time constraint and a maximum reducible time constraint, meaning the minimum and maximum time that can be continuously reducible over the entire dispatch cycle (T=24), as follows.

$$ts_{\min}^{cut}(u_t^{cut} - u_t^{cut}) \le \sum_{t=\tau}^{t+ts_{\min}^{cut}-1} u_t^{cut}, \tau \in \left[1, T - ts_{\min}^{cut} + 1\right] \tag{9}$$

$$1 \le \sum_{t=\tau}^{t+ts_{\max}^{cut}} (1 - u_t^{cut}), t \in \left[1, T - ts_{\max}^{cut}\right] \tag{10}$$

where $ts_{\max}^{cut}$ and $ts_{\min}^{cut}$ are the maximum and the minimum continuous reduction time of the reducible load, respectively.

$$C_{cut} = C_p^{cut} \sum_t u_t^{cut} \alpha^{cut} L_t^{cut} \tag{11}$$

Where C_{cut} and C_p^{cut} are the total compensation cost and the unit compensation cost of the reducible load.

3. Optimal allocation and scheduling of counted and flexible loads

In this paper, the mixed integer linear programming method is used to optimize the configuration and dispatch operation of the integrated energy system, and the economy and environmental protection of the system operation considering the flexible load are considered, to make the optimal results more in line with the actual situation. The system optimization process is shown in Figure

1. In the early stage of the construction of the integrated energy system, the optimal allocation mainly considers the investment cost, operating cost, electricity transaction cost, gas purchase cost and environmental cost. After the actual operation, the investment cost is no longer considered in the scheduling problem, and the flexible load operation constraint and compensation cost target are increased.

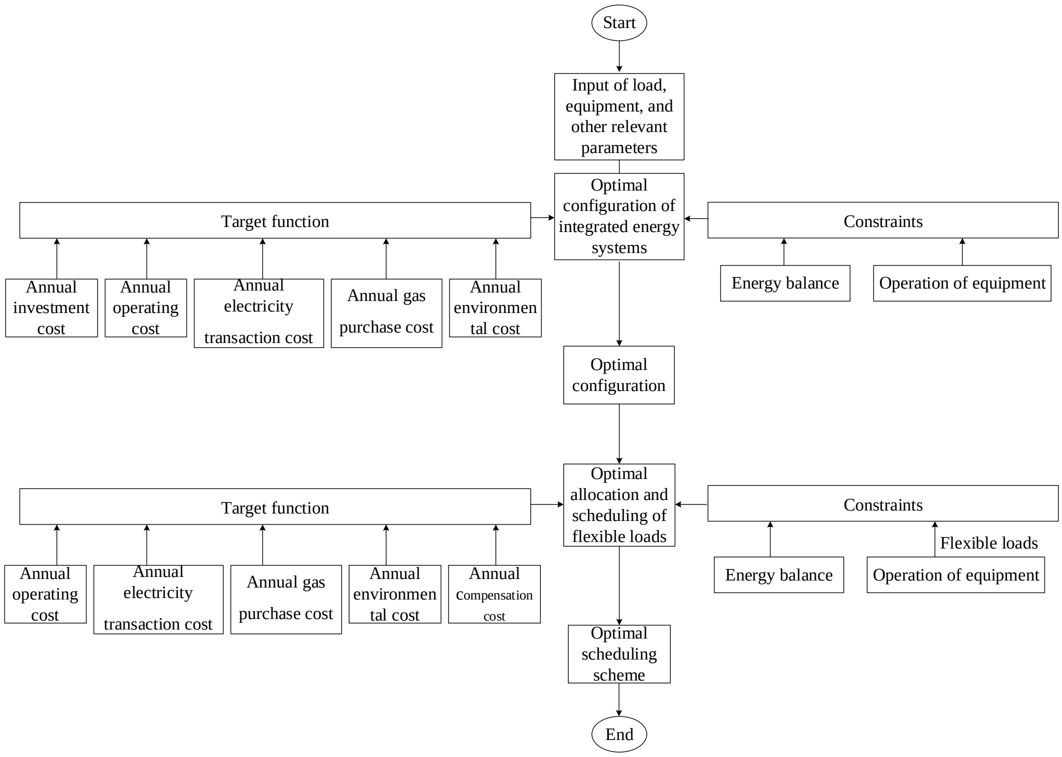

Fig. 1. the integrated energy system optimization process

3.1 Target function

The optimal configuration model of the integrated energy system is constructed by considering the economics of the integrated energy system on the customer side, with the minimum annual operating integrated economic cost of the integrated energy system as the optimization target. For the smoothing, transfer and reduction of flexible load, users need to be compensated, and the size of the compensation cost will affect the optimal configuration and operation of the equipment. Therefore, the integrated economic cost C_{total} should not only includes the annual investment cost C_{inv}, annual operating cost C_{op}, annual electricity transaction cost C_{ele}, annual gas purchase cost C_{gas} and annual environmental cost C_{env}, but also need to include the compensation cost C_{com} as follows.

$$\min C_{total} = C_{inv} + C_{op} + C_{ele} + C_{gas} + C_{env} + C_{com} \tag{12}$$

The individual costing methods are as follows.

1) The annual investment cost is the investment construction cost of each integrated energy system equipment, including discrete equipment gas turbines (GT), gas boilers (GB) and continuous equipment photovoltaic (PV), heat pumps (HP), electric chillers (EC), absorption chillers (AC) and each energy storage equipment (ES), as follows.

$$\begin{cases} C_{inv} = C_{inv}^{GT} + C_{inv}^{GB} + \sum_{dev} C_{inv}^{dev} \\ C_{inv}^{GT} = \sum_{k} n_k^{GT} P_k^{GT} \mu_k^{GT} a_k^{GT} \\ C_{inv}^{GB} = \sum_{k} n_k^{GB} Q_k^{GB} \mu_k^{GB} a_k^{GB} \\ C_{inv}^{dev} = \sum_{dev} c^{dev} \mu^{dev} a^{dev}, dev \in \{PV, HP, EC, AC, EES, TES, CES\} \end{cases} \tag{13}$$

where C_{inv}^{GT}, C_{inv}^{GB}, and C_{inv}^{dev} are the total annual investment costs of discrete equipment GT, GB and continuous equipment dev respectively, n_k^{GT} and n_k^{GB} are the numbers of configurations of the *k*th GT and GB equipment respectively, P_k^{GT} is the rated electrical power of the *k*th GT equipment, μ_k^{GT}, μ_k^{GB}, and μ^{dev} are the unit investment costs of the three types of equipment respectively, a_k^{GT}, a_k^{GB}, and a^{dev} are the equal annual value factors of the three types of equipment respectively, Q_k^{GB} is the rated thermal power of the *k*th GB equipment and c^{dev} is the rated power of the *k*th continuous equipment dev.

The equivalent annual value factor for each item of equipment is calculated as follows.

$$a = \frac{r(1+r)^L}{(1+r)^L - 1} \tag{14}$$

where *r* is the annual interest rate, and *L* is the useful life of the equipment.

2) The operating costs of each item of equipment are calculated as follows.

$$\begin{cases} C_{op} = C_{op}^{GT} + C_{op}^{GB} + \sum_{dev} C_{op}^{dev} \\ C_{op}^{GT} = \sum_{d} \theta_d \sum_{k} \lambda_k^{GT} \sum_{t} p_{k,t,d}^{GT} \\ C_{op}^{GB} = \sum_{d} \theta_d \sum_{k} \lambda_k^{GB} \sum_{t} q_{k,t,d}^{GB} \\ C_{op}^{dev} = \sum_{dev} \sum_{d} \theta_d \lambda^{dev} \sum_{t} p_{t,d}^{dev}, \quad dev \in \{PV, HP, EC, AC, EES, TES, CES\} \end{cases} \tag{15}$$

where C_{op}^{GT} , C_{op}^{GB} , and C_{op}^{dev} are the total annual operating costs of discrete equipment GT, GB, and continuous equipment dev respectively, λ_k^{GT} , λ_k^{GB} , and λ^{dev} are the unit O&M costs of the three types of equipment, *d* is the typical day type; θ_d is the total number of days in a typical day *d*, $p_{k,t,d}^{GT}$, $p_{k,t,d}^{GB}$, and $p_{t,d}^{dev}$ are the power output of the three types of equipment in period *t* under a typical day *d*.

3) The cost of electricity trading is calculated as follows.

$$C_{ele} = \sum_d \theta_d E_d = \sum_d \theta_d (E_d^{im} - E_d^{ex}) = \sum_d \theta_d [\sum_t (\rho_{d,t}^{im} p_{d,t}^{im} - \rho_{d,t}^{ex} p_{d,t}^{ex})] \quad (16)$$

where E_d , E_d^{im} , and E_d^{ex} are the cost of electricity trading, the total cost of electricity purchased and the total revenue from electricity sales on a typical day *d*, $\rho_{d,t}^{im}$, $\rho_{d,t}^{ex}$, $p_{d,t}^{im}$ and $p_{d,t}^{ex}$ are the price of electricity purchased, the price of electricity sold, the amount of electricity purchased and the amount of electricity sold in period *t* on a typical day *d*, respectively.

4) The cost of gas purchase is calculated as follows.

$$C_{gas} = \sum_d \theta_d G_d = \sum_d \theta_d [\sum_t (\rho^{gas} f_{d,t}^{gas})] \quad (17)$$

where G_d is the transaction cost of natural gas on a typical day *d*, ρ^{gas} is the unit calorific value price, $f_{d,t}^{gas}$ is the power purchased in period *t* on a typical day *d*.

5) The environmental cost is measured through a carbon tax, which considers CO_2 emissions in the form of both externally purchased and internally generated electricity for an integrated energy system, calculated as follows.

$$C_{env} = \varphi \sum_d \theta_d \sum_t (Z^{im} p_{d,t}^{im} + Z^{GT} \sum_k p_{k,d,t}^{GT}) \quad (18)$$

where φ is the carbon tax, Z^{im} is the carbon emission intensity of purchased electricity, and Z^{GT} is the carbon emission intensity of electricity generated by GT equipment within an integrated energy system.

Considering that when the system is put into operation, all the equipment has already been configured and there is no need to consider the investment cost, therefore, only the annual operation and maintenance cost, annual electricity purchase and sale cost, annual gas purchase cost, annual environmental cost, and annual compensation cost are considered for the optimal scheduling of the integrated energy system as follows.

$$\min C_{total} = C_{op} + C_{ele} + C_{gas} + C_{env} + C_{com} \quad (19)$$

3.2 Constraints

1) Electric power balance constraint

When accounting for electrical flex loads, at any time under any typical day, the system shall satisfy the electrical power balance including the flex load as follows.

$$\begin{aligned}&\sum_k p_{k,d,t}^{GT}+\sum_k p_{d,t}^{PV}+p_{d,t}^{im}-p_{d,t}^{ex}+p_{EES,d,t}^{dis}-p_{EES,d,t}^{cha}=PL_{d,t}+\sum_k p_{d,t}^{EC}+\sum_k p_{d,t}^{HP}\\&PL_{d,t}=P_{d,t}^{0}+\sum_k P_{d,t,k}^{shift}+\sum_k P_{d,t,k}^{trans}+P_{d,t}^{cut}\end{aligned}\tag{20}$$

where $P_{d,t}^{0}$ is the fixed load power at time t on a typical day d.

2) Thermal power balance constraint

$$\sum_k q_{k,m,d,t}^{GT}+\sum_k q_{k,m,d,t}^{GB}+\sum_k q_{d,t}^{HP}+p_{TES,d,t}^{dis}-p_{TES,d,t}^{cha}=QL_{d,t}+\sum_k p_{d,t}^{AC}\tag{21}$$

3) Cold power balance constraint

$$r_{d,t}^{AC}+r_{d,t}^{EC}+r_{d,t}^{HP}+p_{CES,d,t}^{dis}-p_{CES,d,t}^{cha}=CL_{d,t}\tag{22}$$

4) Fuel power balance constraint

$$\begin{cases}f_{d,t}^{gas}=\sum_k f_{k,d,t}^{GT}+\sum_k f_{k,d,t}^{GB}\\ f_{k,d,t}^{GT}=p_{k,d,t}^{GT}/\eta_k^{GT}\\ f_{k,d,t}^{GB}=p_{k,d,t}^{GB}/\eta_k^{GB}\end{cases}\tag{23}$$

5) GT equipment operation constraints

$$\alpha_{\min,k}^{GT}n_k^{GT}P_k^{GT}\le p_{k,d,t}^{GT}\le n_k^{GT}P_k^{GT}\tag{24}$$

$$q_{k,d,t}^{GT}=\omega_k^{GT}p_{k,d,t}^{GT}\beta_k^{GT}\tag{25}$$

6) GB equipment operation constraints

$$\alpha_{\min,k}^{GB}n_k^{GB}Q_k^{GB}\le q_{k,d,t}^{GB}\le n_k^{GB}Q_k^{GB}\tag{26}$$

7) PV equipment operation constraints

$$p_{d,t}^{PV}=\begin{cases}c^{PV}\dfrac{S_{d,t}}{S},0\le S_{d,t}\le S\\ c^{PV},S_{d,t}>S\end{cases}\tag{27}$$

8) HP equipment operation constraints

On a typical winter day (d=1), the HP plant produces heat with the following operating constraints.

$$\begin{cases}0\le r_{d,t}^{HP}\le c^{HP}\\ q_{d,t}^{HP}=p_{d,t}^{HP}\lambda_{cop}^{HP,h},d=1\\ r_{d,t}^{HP}=0\end{cases}\tag{28}$$

On a typical day in summer (d=2) and a typical day in the transitional season (d=3), the HP plant cools with the following operating constraints.

$$\begin{cases} 0 \le q_{d,t}^{HP} \le c^{HP} \\ r_{d,t}^{HP} = p_{d,t}^{HP} \lambda_{cop}^{HP,c}, d = 2,3 \\ q_{d,t}^{HP} = 0 \end{cases} \tag{29}$$

9) EC equipment operation constraints

$$0 \le r_{d,t}^{EC} \le c^{EC} \tag{30}$$

$$r_{d,t}^{EC} = \lambda_{cop}^{EC} p_{d,t}^{EC} \tag{31}$$

10) AC equipment operation constraints

$$0 \le r_{d,t}^{AC} \le c^{AC} \tag{32}$$

$$r_{d,t}^{AC} = \lambda_{cop}^{AC} p_{d,t}^{AC} \tag{33}$$

11) ES equipment operation constraints

$$E_{k,d}^{0} = r_k^0 c_k^{ES} \tag{34}$$

$$E_{k,d,t=T} = E_{k,d}^{0} \tag{35}$$

$$E_{k,d,t} = \begin{cases} (1-\varsigma_k) E_{k,d}^{0} + p_{k,d,t}^{cha} \eta_k^{cha} - \dfrac{p_{k,d,t}^{dis}}{\eta_k^{dis}}, t = 1 \\ (1-\varsigma_k) E_{k,d,t-1} + p_{k,d,t}^{cha} \eta_k^{cha} - \dfrac{p_{k,d,t}^{dis}}{\eta_k^{dis}}, t > 1 \end{cases} \tag{36}$$

$$\omega_k^{\min} c_k^{ES} \le E_{k,d,t} \le \omega_k^{\max} c_k^{ES} \tag{37}$$

$$p_{k,d,t}^{c} \le v_k^{\min} c_k^{ES} \tag{38}$$

$$p_{k,d,t}^{d} \le v_k^{\max} c_k^{ES} \tag{39}$$

12) Electric power exchange constraint

$$0 \le p_{d,t}^{im} \le u_{d,t}^{ele} p_{d,t}^{im,\max} \tag{40}$$

$$0 \le p_{d,t}^{ex} \le (1- u_{d,t}^{ele}) p_{d,t}^{ex,\max} \tag{41}$$

4. Calculated examples

4.1 Flexible load parameters

The parameters of the flexible loads are shown in Tables 1 to 3 for shiftable loads, transferable loads, and reducible loads in the winter, summer, and transition seasons, respectively.

Table 1

Shiftable load parameters.

Type of load	Typical day	Start periods	Scheduling periods	Running time(h)	Power rating(kW)	Compensation cost(Dollar /kWh)

Shiftable loads 1	d=1	20	[5,24]	3	400	0.007
Shiftable loads 2	d=2	9	[5,24]	3	400	0.007
Shiftable loads 3	d=3	11	[5,24]	3	300	0.007

Table 2

Transferable load parameters.

Type of load	Typical day	Duration	Power rating(kW)	Min. transfer Power (kW)	Max. transfer Power (kW)	Compensation cost(Dollar /kWh)
Transferable loads 1	d=1	16, 17, 18	[5,22]	800	50	0.012
Transferable loads 2	d=2	12, 13, 14	[5,22]	900	50	0.012
Transferable loads 3	d=3	8, 9, 10	[5,22]	600	80	0.012

Table 3

Reducible load parameters.

Type of load	Typical day	Reduction factor	Min. reduction time(h)	Max. reduction time (h)	Compensation cost(Dollar /kWh)
Reducible loads 1	d=1	0.7	2	5	0.044
Reducible loads 2	d=2	0.6	2	5	0.044
Reducible loads 3	d=3	0.5	2	5	0.044

Figure 2 below shows the flexible load distribution under different typical days.

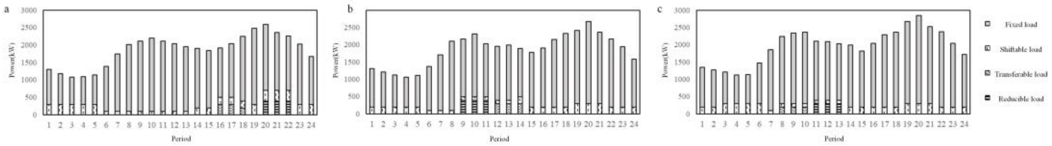

Fig. 2. (a) typical day in summer; (b) typical day in winter; (c) typical day in the transitional season.

4.2 Optimal configuration results

Under the above conditions, the integrated energy plant is configured as a conventional supply plant + renewable supply plant (PV and HP) + energy storage plant (EES, TES, and CES) and the optimal configuration of the integrated energy system is calculated using mixed integer linear programming. The results are shown in Table 4. It can be seen that setting a flexible load for the same total load can lead to a reduction in the total annual cost. At this point, the annual investment cost, annual operating cost, and annual environmental cost are all reduced, and the system can capture more revenue from electricity trading due to the nature of the flexible load; however, the system's demand for natural gas increases and the annual gas purchase cost rises.

Table 4

Integrated energy system configuration costs with flexible loads.

With or without flexible load	Annual investment cost (Dollar)	Annual operating cost (Dollar)	Annual electricity transaction cost (Dollar)	Annual gas purchase cost (Dollar)	Annual environmental cost (Dollar)	The annual integrated economic cost(Dollar)	Rate of cost reduction (Dollar)
without	762161.76	230455.88	-59750.00	1146794.12	9264.71	-2088941.18	-
with	498779.41	222544.12	-172764.71	1264691.18	8661.76	-1821926.47	12.78%

In conjunction with the system configuration options in Table 5, the demand for thermal energy utilization equipment is reduced when taking into account the electric flex load, with the two gas turbines (GT) in the no flex load option being reduced to one, and the absorption chillers (AC) and thermal energy storage (TES) being similarly reduced, while the electrical energy equipment is increased accordingly, with the heat pump (HP) increasing from 588kW to 1087kW, while the electrical energy storage is still heavily deployed when taking into account the electric flex load, despite its higher cost than other energy storage.

Table 5

Integrated energy system configuration capacity with flexible loads.

With or without flexible load	GT(kW)	EC(kW)	AC(kW)	HP(kW)	PV(kW)	EES(kW)	TES(kW)	CES(kW)
with	2420	732	1664	588	4707	571	2357	2152
without	1210	786	823	1087	5000	2998	179	0

4.3 Optimal scheduling results

4.3.1 Unit operation scheduling situation

Figures 3-5 below show the dispatch of equipment on a typical winter day, a typical summer day, and a typical day during the transition season. As there is no cold load on a typical winter day, only the dispatch of electrical and thermal equipment is analyzed.

As can be seen from Figure 3(a), the system sells zero electricity on a typical winter day. During the "valley" hours, the system supplies electricity mainly through electricity purchases, with the largest amount of electricity purchased in time slot 7. Due to the low purchase price in the morning, the system charges the EES in hours 5, 6, and 7. Due to the higher purchase price and insufficient light intensity in hours 8 and 9, the PV is unable to generate sufficient power and the EES is discharged to supply the electricity in these hours. After time slot 10, the PVs increase their power generation and take on the main supply task. In time slots 13, 14, and 16, there is sufficient power, and the system again stores energy through the EES. During hour 17, as the heat load demand gradually increases and the light intensity becomes progressively less, the system tends to use the GT to generate electricity to meet both the supply and the heat demand, and to store energy electrically during hour 17 to meet the electricity demand in the evening hours 19 and 21. During the evening hours, the system relies primarily on electricity purchased from the grid and GT generation.

As can be seen from Figure 3(b), the dispatch of thermal energy equipment is strongly influenced by the power mix. Between periods 1 and 7, the GT output is low, and the thermal load is mainly supplied by HP, with thermal storage used to assist in supplying energy during periods 1, 2, and 3. In periods 8, 9, and 10, all heat is supplied by GT due to higher electricity purchase costs and increased HP operating costs. In the afternoon, the intensity of PV increases and the cost of electricity decreases, so HP resumes most of the heating duties. After 17.00 hours, the heating mix is again adjusted, when the gas turbines operate at full capacity and take on both the electrical and thermal energy supply, with the shortfall being made up by the heat pump HP and the thermal storage TES. On a typical winter day, the thermal energy storage TES stores energy mainly during the morning hours 5 to 10 and hour 17 to meet the heating demand throughout the day.

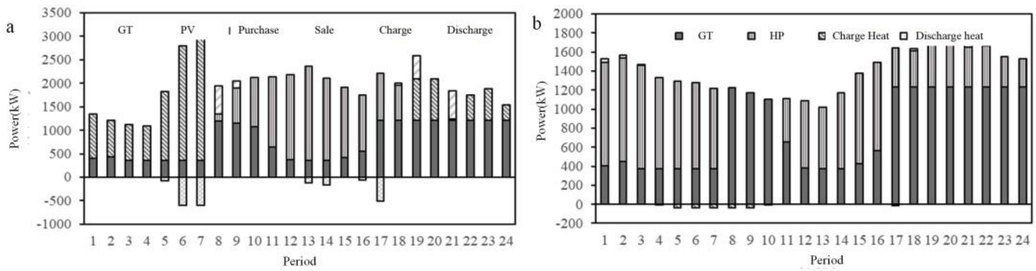

Fig. 3. (a) dispatch operation of power plants; (b) dispatch operation of thermal energy plants.

Under a typical summer day, the dispatch of electrical energy equipment is relatively similar for periods 1-6, with a GT power of approximately 400kW, in conjunction with a large number of system purchases to meet the electrical load demand. From period 7 onwards, the PV starts to generate electricity and the EES carries out the first energy storage of the day. In the period from time slot 8 to time slot 18, the system no longer purchases electricity due to higher electricity prices, and the PV and GT are mainly used to supply electricity. In time slots 8, 11, 12, and 16, the EES discharge is flexibly regulated to avoid high electricity purchase costs. During periods 11 to 16, the system sells excess electricity online after meeting the needs of the EES, as the electricity supply is sufficient. During and after hour 19, the system relies on grid purchases and GT generation, but with an increased proportion of GT generation compared to the early morning hours, and with EES discharge participating in the electricity supply during hours 19 and 21.

On a typical summer day, the heating mix is more homogeneous. As HP is no longer involved in heating and the system is not equipped with GB, the GT takes on the main heating task and the TES is supplemented by regulation. The TES is involved in charging and discharging energy several times, storing heat in periods 8, 11, 12, 16, 18, 19, 23, and 24 and discharging heat in periods 1, 2, 3, 10, 13, 14, 20 and 21, with extremely flexible operation.

As can be seen in Figure 4(c), the HP supply cooling power is more stable during a typical summer day, maintaining about half of the share due to its higher cooling efficiency. During periods 1 to 10, it is the EC that mainly takes care of the rest of the cooling supply. The cooling power of the AC is closely related to the heating power of the GT, which takes up a larger share of the heating in periods 11, 12, and 16 and periods 18 to 24, thus replacing the EC with the AC as the main cooling unit.

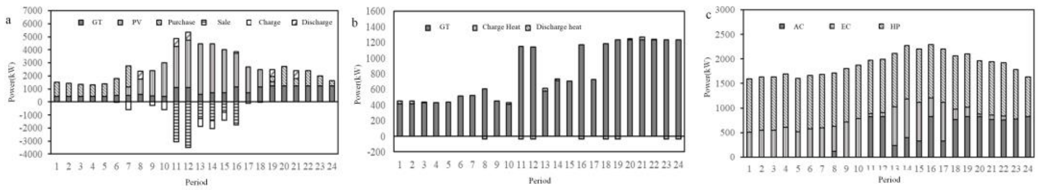

Fig. 4. (a) dispatch operation of power plants; (b) dispatch operation of thermal energy plants; (c) dispatch operation of cold energy plants.

Under a typical day of the transition season, the scheduling of electrical energy equipment can be divided into the early morning hours (periods 1-5), the morning hours (periods 6-7), the photovoltaic hours (periods 8-18) and the evening hours (periods 19-24), the characteristics of each period are similar to those of a typical summer day, but compared to a typical summer day, the typical day of the transition season is dominated by GT generation, as opposed to the morning hours, for the following reasons. The reason for this is that the thermal load power increases compared to a typical summer day and GT operation can meet both the thermal demand, especially in the early morning and late evening hours when the share of purchasing power is squeezed.

The thermal energy supply on a typical day in the transitional season is also dominated by GT, with flexible scheduling of thermal energy storage, similar to a typical summer day. However, in the cold load dispatch, HP supplies a large proportion of the cold load, while EC and suction AC only have a small amount of output during some hours, mainly because of the heat demand of the system during the typical day of the transitional season make GT supply a larger proportion of the energy, and the cheap cost of electricity and high cooling efficiency make HP the most important energy supply equipment, with a proportion of over 90% of the energy supplied throughout the day.

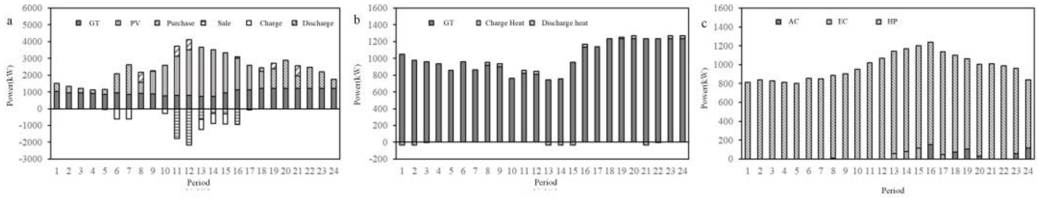

Fig. 5. (a) dispatch operation of power plants; (b) dispatch operation of thermal energy plants; (c) dispatch operation of cold energy plants.

4.3.2 Flexible loads dispatching situation

Table 6 below shows the dispatch situation of the shiftable loads. On a typical winter day, shiftable load 1 originally running in the 20, 21, and 22 hours is scheduled to the 5, 6, and 7 hours, which, when combined with Figure 3(a), shows that the system increases power purchases to meet the demand for shiftable load, but at this time the purchase price of electricity is lower and shifting to this time can better control the purchase cost. Under typical days in the summer and transition seasons, the shiftable load operating in the morning hours is dispatched to the late afternoon hours of 13, 14, and 15, when PV generation is higher due to high light intensity and the fixed electrical load demand is not as high, allowing for better peak shaving and valley filling.

Table 6

Shiftable loads dispatch situation.

Type of load	Typical day	Pre-dispatch periods	Post-dispatch periods	Power rating (kW)	Compensation cost (Dollar)
Shiftable loads 1	d=1	20	20, 21, 22	5, 6, 7	8.58
Shiftable loads 2	d=2	9	9, 10, 11	13, 14, 15	8.58
Shiftable loads 3	d=3	11	11, 12, 13	13, 14, 15	6.43

Table 7 below shows the dispatch situation of the transferable loads. The dispatch situation of transferable loads is similar to that of shiftable loads on typical days in the winter and transitional seasons, with the post-dispatch periods mainly concentrated in the morning and late afternoon. On the other hand, on a typical day in summer, due to the large transferable load and the limitation of the upper limit of transferable load dispatch, two additional periods of 9 and 10 a.m. are added to the dispatch of transferable load in addition to the morning and afternoon periods, when the light intensity gradually increases and PV generation can be fully utilized and the load power distribution is more flexible.

Table 7

Transferable loads dispatch situation.

Type of load	Typical day	Pre-dispatch periods	Post-dispatch periods (Power rating/kW)	Compensation cost (Dollar /kWh)

Transferable loads 1	d=1	16, 17, 18	5(200), 6(200), 7(200), 12(50), 13(150)	137.22
Transferable loads 2	d=2	12, 13, 14	5(50), 6(50), 7(150), 9(50), 10(150), 13 (150), 14 (150), 15 (150)	185.25
Transferable loads 3	d=3	8, 9, 10	13(200), 14(200), 15(200)	149.23

Table 8 shows the dispatch situation for reducible loads. It can be seen that the reducible load is curtailed in the majority of periods as the cost of supplying the reducible load is generally greater than its compensation cost. Only reducible load 1 is not curtailed in periods 6, 7, 13, and 19; reducible load 2 is not curtailed in periods 6, 12, 17, and 22; and reducible load 3 is not curtailed in periods 1, 7, 13, 17 and 23. The supply of electricity is greater than the demand during these periods and can be balanced by the reducible load. Compare the above flexible load dispatch situation with the total load before dispatch, as shown in Figure 6.

Table 8

Reducible loads dispatch situation.

Periods	Reducible loads 1(kW)			Reducible loads 2(kW)			Reducible loads 3(kW)		
	Before	After	Whether to reduce	Before	After	Whether to reduce	Before	After	Whether to reduce
1	300	90	Yes	200	80	Yes	200	200	No
2	300	90	Yes	200	80	Yes	200	100	Yes
3	300	90	Yes	200	80	Yes	300	150	Yes
4	300	90	Yes	200	80	Yes	300	150	Yes
5	300	90	Yes	200	80	Yes	300	150	Yes
6	100	100	No	100	100	No	300	150	Yes
7	100	100	No	100	40	Yes	100	100	No
8	100	30	Yes	100	40	Yes	100	50	Yes
9	100	30	Yes	100	40	Yes	100	50	Yes
10	100	30	Yes	100	40	Yes	100	50	Yes
11	100	30	Yes	100	40	Yes	100	50	Yes
12	100	30	Yes	100	100	No	100	50	Yes
13	100	100	No	100	40	Yes	100	100	No
14	200	60	Yes	200	80	Yes	200	100	Yes
15	200	60	Yes	200	80	Yes	200	100	Yes
16	200	60	Yes	200	80	Yes	200	100	Yes
17	200	60	Yes	200	200	No	200	200	No
18	200	60	Yes	200	80	Yes	200	100	Yes
19	300	300	No	300	120	Yes	300	150	Yes
20	300	90	Yes	300	120	Yes	300	150	Yes
21	300	90	Yes	300	120	Yes	300	150	Yes
22	300	90	Yes	200	200	No	200	100	Yes
23	300	90	Yes	200	80	Yes	200	200	No
24	300	90	Yes	200	80	Yes	200	100	Yes

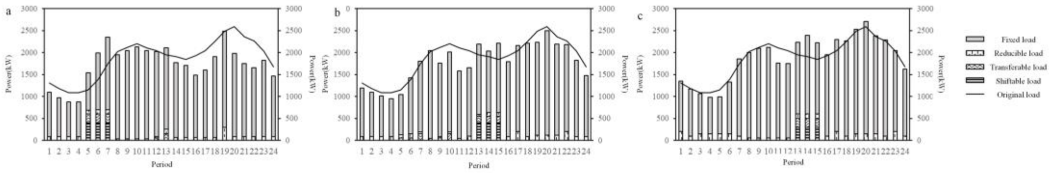

Fig. 6. (a) typical day in winter; (b) typical day in summer; (c) typical day in the transitional season.

4.3.3 System dispatch costs

As shown in Table 9, setting some of the fixed loads as flexible loads can reduce the total annual cost for the same electrical, thermal and cooling load power. In this example, adding flexible loads can effectively reduce electricity transaction costs and environmental costs.

Table 9

Integrated energy system dispatch costs with flexible loads.

With or without flexible load	Annual operating cost (Dollar)	Annual electricity transaction cost(Dollar)	Annual gas purchase cost(Dollar)	Annual environmental cost (Dollar)	Annual compensation cost (Dollar)	Annual dispatch cost (Dollar)	Rate of cost reduction
without	199294.1	319147.1	782235.3	12117.6	-	1312794.1	-
with	199926.5	264661.8	788955.9	11264.7	44573.5	1309397.1	0.26%

5. Conclusions

In this paper, the optimal dispatching of flexible loads for electricity is studied, the optimal allocation of the system with the economy in mind is calculated using mixed integer linear programming, and the optimal dispatching of flexible loads and integrated energy unit equipment is carried out for the optimal solution, with the following conclusions.

1) The setting of flexible loads can reduce the total cost of integrated energy system configuration. Due to the adjustable characteristics of the flexible load, the system can obtain more revenue from electricity trading, and the annual investment cost, annual operation cost, and annual environmental cost are all reduced. It is worth noting that at this time the system has increased demand for natural gas.

2) On a typical winter day, shiftable load and transferable load are mainly dispatched in the morning hours, when the purchase price is lower and the purchase cost can be better controlled; on a typical summer and transition season day, the shiftable load is dispatched to the late afternoon hours, when PV generation is more available and the cost of energy is cheaper; the reducible load is reduced for most of the time on different typical days.

3) The deployment of flexible loads can reduce the dispatch costs of the system, mainly in terms of the reduction of electricity transaction costs and environmental costs.

REFERENCES

[1]. *Naoui M.A et al.* Integrating iot devices and deep learning for renewable energy in big data system. UPB Scientific Bulletin, Series C: Electrical Engineering and Computer Science, 82 (3) ,251-266,2020.
[2]. *Li Zesen et al.* Research on evaluation index system of new power system. 122442X-122442X-8, 2022
[3]. *Wang Xiaohui et al.* Research on multi-objective planning and optimization of integrated energy system based on economy and environmental protection. E3S Web of Conferences, 245:01039, 2021
[4]. *Zhang Hongye et al.* Energy Storage Configuration of An Integrated Energy System Considering the Response of Air-Conditioning Load and The Uncertainty of Source-Load. Journal of Physics: Conference Series, 2022(1), 2021
[5]. *Stennikov Valery et al.* Current state of research on the energy management and expansion planning of integrated energy systems. Energy Reports, 8:10025-10036, 2022
[6]. *Guo Yongtao and Xiang Yue*. Low-Carbon Strategic Planning of Integrated Energy Systems. Frontiers in Energy Research, 2022
[7]. *Hu Hejuan et al*. Enhanced evolutionary multi-objective optimization-based dispatch of coal mine integrated energy system with flexible load. Applied Energy, 307, 2022
[8]. *Wu Xiaonan et al*. Multi-objective and multi-algorithm operation optimization of integrated energy system considering ground source energy and solar energy. International Journal of Electrical Power and Energy Systems, 144, 2023
[9]. *Wang Jiangjiang et al*. Leveraging heat accumulation of district heating network to improve performances of integrated energy system under source-load uncertainties. Energy, 252, 2022
[10]. *Li Hang et al*. Probabilistic energy flow calculation for regional integrated energy system considering cross-system failures. Applied Energy, 308, 2022
[11]. *Xu Wei et al*. Analysis for the Hierarchical and Distributed Coordination Control Method of Integrated Energy Systems. IOP Conference Series: Earth and Environmental Science, 696(1):012004, 2021
[12]. *Xiong Junjie et al*. Multi-stage equipment optimal configuration of park-level integrated energy system considering flexible loads. International Journal of Electrical Power and Energy Systems, 140, 2022
[13]. *Shen Haotian et al*. Multi-objective capacity configuration optimization of an integrated energy system considering economy and environment with harvest heat. Energy Conversion and Management, 269, 2022
[14]. *Guo Jinrui et al.* Optimal dispatching of integrated energy system considering flexible load. Journal of Physics: Conference Series, 2076(1), 2021
[15]. *Huang Qi et al.* Community Flexible Load Dispatching Model Based on Herd Mentality. Energies, 15(13), pp. 4546-4546, 2021
[16]. *Chen Jiming et al.* Day-Ahead Optimal Scheduling of an Integrated Energy System Based on a Piecewise Self-Adaptive Particle Swarm Optimization Algorithm. Energies, 15(3):690-690, 2022
[17]. *Dong Bei et al*. The technique of day-ahead optimized scheduling with multi-type of flexible loads. Electric Power Engineering Technology 37(06):97-102, 2018

[18]. *Zhao Dongmei et al*. Coordinated scheduling model with multiple time scales considering response uncertainty of flexible load. Automation of Electric Power Systems 43(22):21-30, 2019

[19]. *Yang Shengchun et al*. Model and strategy for multi-time scale coordinated flexible load interactive scheduling. Proceedings of the CSEE 34(22):3664-3673, 2014

[20]. *Jiang Yuechun et al*. Integrated energy collaborative optimal dispatch considering human comfort and flexible load. Electric Power Automation Equipment 39(08):254-260, 2019

[21]. *G. C. Lazaroiu et al*. Stochastic optimization of microgrids with renewable and storage energy systems, 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 2016, pp. 1-5

[22]. *G. C. Lazaroiu et al.* Virtual power plant with energy storage optimized in an electricity market approach, 2015 International Conference on Clean Electrical Power (ICCEP), Taormina, Italy, 2015, pp. 333-338