Contents lists available at GrowingScience

International Journal of Industrial Engineering Computations

homepage: www.GrowingScience.com/ijiec

Regulation strategy of an integrated energy system considering the dynamic change of electricity price in the spot market in the day-ahead and in the middle of the day

Jingshuai Pang[a,b], Hongyin Chen[a,b*], Zhenlan Dou[c], Songcen Wang[a,b], Chunyan Zhang[c], Jianfeng Li[a,b], Yang Liu[a,b] and Yi Guo[a,b]

[a]*National Key Laboratory of Power Grid Safety, Beijing 100192, China*
[b]*China Electric Power Research Institute, Beijing 100192, China*
[c]*State Grid Shanghai Municipal Electric Power Company, Shanghai 200122, China*

C H R O N I C L E

Article history:
Received March 2 2025
Received in Revised Format May 9 2025
Accepted May 20 2025
Available online May 20 2025

Keywords:
Spot markets
Electricity prices
Regulation
Stochastic evolutionary games
Integrated energy systems

A B S T R A C T

Most of the renewable energy sources have unstable supply and high volatility. With the growing share of renewable energy in the integrated energy system, it is more and more difficult to execute the energy pre-dispatch regulation decision of the integrated energy system. To address the problem of increased volatility of the system, the study proposes to optimize the pre-dispatch decision-making of the system's control center by analyzing the difference between the day-ahead market clearing price and the declared price of electricity supply. The results show that the node declared power is much higher than the ground's actual clearing power during the period from 1:00 am to 4:00 am. During this period the declared power of the nodes is at 2500kW and the actual clearing power of the nodes is around 1500kW. The outgoing power of the integrated energy system electrical load can be reduced in advance during the period from 10 am to 3 pm. The proposed pre-dispatch decision of the integrated energy system on the basis of the difference between the day-ahead clearing price and the node declared price can ensure the stability of the system operation while reducing the operating cost of the integrated energy system.

1. Introduction

The spot market is a market where energy products are delivered immediately or in a brief span of time after the transaction has been completed. In the spot market, energy prices fluctuate in real time in response to supply and demand (S & D) (Wu et al., 2022). The balance between S & D is particularly important for electricity, an energy source that cannot be stored on a large scale. When market prices are high, power plants may increase production to improve revenues, while users may reduce usage to control consumption costs. This regular price fluctuation effectively maintains the balance between S & D in the electricity market (Li et al., 2022; Ge et al., 2021a). With the rapid economic development and increasing energy demand, the share of renewable energy (RE) in modern energy systems is rising. Because of the volatility and uncertainty of RE output, their performance in the spot market has a significant impact on electricity prices (Cao et al., 2020; Li et al., 2021). When market prices are high, integrated energy systems (IESs) can increase the supply of RE, reducing costs and carbon emissions. However, this kind of regulation strategy, which changes the output of various energy sources, is difficult to control and can easily disrupt the energy supply-demand balance in the original market. To address the issue of volatility and uncertainty of RE output in IES, which leads to irregular fluctuation of electricity price in the spot market and affects the balance of S & D in the electricity market. Based on the IES flexible loads, the study constructs a decision model of autonomous offer in the spot market before the IES day, and based on the model, a multi-objective optimal regulation decision of cooperative dispatch with the goal of reducing the IES operation cost, environmental management cost and fluctuation control cost is formulated. The study innovatively considers the dynamic changes of spot market electricity prices in the integrated scheduling and control strategy of the IES. It realizes the dependable functioning of IES and reduces the fluctuation control cost of IES. This study will be carried out in four parts, the first part is an overview of the current status of the research on IES, the dynamic changes of spot market electricity prices and flexible loads, the second part is a study on the intraday electricity price forecasting and

* Corresponding author
E-mail sysu_ag@126.com (H. Chen)
ISSN 1923-2934 (Online) - ISSN 1923-2926 (Print)
2025 Growing Science Ltd.
doi: 10.5267/j.ijiec.2025.5.004

dispatch decision-making of IES, the third part is the experimental validation and analysis of the model constructed by the study, and the last part is an overview summary of the study.

2. Related works

IES is the current mainstream power supply system, to meet the challenge of ultra-high penetration of RE, Pan G et al. proposed an integrated electricity-hydrogen energy system planning model that considers hydrogen production and storage technologies. The results show that the model can robustly cope with generation load uncertainty, improve system reliability, and optimize small hydropower allocation and operation, providing an effective method for energy system planning (Pan et al., 2020). Cao M et al. proposed an emergency dispatch formula based on the dynamic optimal energy flow of IES and constructed a reliability assessment framework to mitigate the risk of IES operation and improve the reliability of energy supply. The outcomes indicate that the model can validly raise the operational stability of IES (Cao et al., 2021). To address the issues of energy efficiency and environmental pollution, a two-tier optimal dispatch model for multi-objective vehicle charging stations and community IES is developed, and a dynamic pricing mechanism combining time-sharing and real-time pricing is proposed. The results show that the method balances the allocation of car charging stations and community IESs by coordinating flexible demand response and RE uncertainty (Li et al., 2021). Sun P et al. raised a model for minimizing the total annual cost considering the carbon trading cost to study the low-carbon economic operation of IESs. The outcomes denote that the carbon trading mechanism not only effectively reduces carbon emissions, but also reduces the total annual cost, and the ground source heat pump and electric refrigeration unit can reduce the fluctuation caused by the change of natural gas price (Sun et al., 2021). Azuatalam D et al. raised a flexible load forecasting framework based on a nonparametric Bayesian model in order to statistically characterize the trajectory of flexible loads in distributed energy sources. The results show that the framework can effectively count the flexible load trajectories in distributed energy systems (Azuatalam et al., 2020). To raise the preciseness of short-term electricity load predictions and solve the problem of dramatic changes in electricity consumption due to various factors. A hybrid model on the basis of variational mode decomposition and long short-term memory was proposed by Lv et al. The outcomes denote that the prediction accuracy of the model is higher than that of the comparison model, which verifies its effectiveness and practicality (Lv et al., 2021).

Spot market can reflect S & D, to investigate the feasibility of cloud computing providers to offer a spot market, the profit optimization problem is modeled by combining queuing theory and game theory. Easy-to-check conditions are proposed to evaluate provider profit and user experience. The results show that providing a spot market achieves profit growth and creates Pareto improvements for users when specific conditions are met (Dierks & Seuken, 2022). Ameur H B et al. proposed a methodology using a nonlinear autoregressive distributed lag framework to study the relationship between spot and futures commodity markets. The results show that there is a bi-directional relationship between the futures market and the spot market, and the leading effect of the futures market is more significant, which confirms the dominant role of the futures market in the price discovery of commodities (Ameur et al., 2022). In order to analyze the development of the hydropower market, Lin L et al. use the evolutionary game analysis, and they put forward the idea that the PAB settlement method is beneficial for the stabilization of the price of electricity when there is a shortage of power supply. The results show that when the supply of electricity exceeds the demand, the market settlement tariff will be lower than the bidding feed-in tariff, which helps stabilize and balance the development of the electricity market (Lin et al., 2020). To investigate the price leadership dynamics between Kuala Lumpur index futures and its underlying spot market, high frequency data and maximum overlap discrete wavelet transform methods were used. The idea that price discovery is a scale-dependent phenomenon is presented. The findings denote that the futures market lags behind the spot market in price formation and suggests arbitrage opportunities in high frequency trading (Sifat et al., 2021).

In summary, the energy scheduling problem of IES has been a key research direction that requires urgent resolution. Most of the current IES energy dispatch studies focus on load forecast optimization or reducing system carbon emissions, and there are fewer studies on reducing the magnitude of IES fluctuations. Therefore, the study proposes to optimize the IES mid-day dispatch decision-making system starting from the electricity price fluctuation in the spot market.

2. IES regulation decision-making based on dynamic changes in electricity prices

Price fluctuations in the electricity market are the main reason for dispatch control in the IES. The study analyzes the market prices and constructs a day-ahead market (DAM) autonomous offer decision model based on flexible loads. And based on this DAM autonomous offer decision model, the study analyzes the IES integrated dispatch control decision.

2.1 Decision-making model of autonomous offer in the DAM based on flexible loading

As people's living standards continue to increase, the number of household large-scale electric equipment, such as air conditioners, washing machines, new energy vehicles and other equipment, is also increasing, and the load on the electric power system is also increasing (Basit et al., 2020). The loads generated by the operation of these domestic large-scale electric equipment are called flexible loads (Perera et al., 2020). Flexible loads include interruptible loads and shiftable loads. Interruptible loads can be curtailed or interrupted based on scheduling needs, and leveling loads can be shifted from one time

period to another during the scheduling period of the scheduling curve, and the maximum load cannot be reduced or increased (Zhang et al., 2021; Shi et al., 2022). Flexible load aggregators need to forecast power offers from other load aggregators and give their own offers based on day-ahead dispatchable capacity. After collecting all the offers, the power trading center clears them based on the market declaration and the load aggregator settles them based on the marginal tariff of the node where it is located. In this process, the load aggregator needs to compress the node power purchase cost as much as possible, based on this goal, the research constructs the objective function (OF) shown in Eq. (1).

$$\min F_j^{DA} = \sum \left(\pi_{j,t}^{DLMP} P_{j,t}^{H} \Delta t + \pi_{j,t}^{DLMP} \left(P_{j,t}^{ch} - P_{j,t}^{dis} \right) \Delta t \right) \tag{1}$$

In Eq. (1), $\min F_j^{DA}$ denotes the load aggregator OF; j denotes the load aggregator; t denotes the time period; $\pi_{j,t}^{DLMP}$ denotes the DAM clearing tariff; $P_{j,t}^{H}$ denotes the day-ahead energy plan of the node's flexible loads; $P_{j,t}^{ch}$ denotes the charging plan of the aggregator's node's flexible loads; and $P_{j,t}^{dis}$ denotes the aggregator's node's flexible loads' discharging plan. The constraints of the flexible load offer decision model are shown in Eq. (2) (Ge et al., 2021b).

$$\pi_{j,\min}^{DA} \le \pi_{j,t}^{DA} \le \pi_{j,\max}^{DA} \qquad \forall j \in N^{LA}, \forall t \in T \tag{2}$$

In Eq. (2), $\pi_{j,\min}^{DA}$ denotes the lowest offer in the DAM; $\pi_{j,\max}^{DA}$ denotes the highest offer in the DAM; $\pi_{j,t}^{DA}$ denotes the DAM offer; N^{LA} denotes the set of aggregator nodes; and T denotes the flexible load period. Market clearing needs to consider the safety calibration and social welfare, therefore, the OF of the DAM clearing model established in the study is shown in Eq. (3).

$$\min f^{DA} = \left(\sum_{t \in T} \sum_{m \in N^S} \pi_m^G P_{m,t}^G \Delta t - \sum_{t \in T} \sum_{j \in N^{LA}} \pi_{j,t}^{DT} \left(P_{j,t}^{ch} - P_{j,t}^{dis} \right) \Delta t - \sum_{t \in T} \sum_{m \in N^S} \pi_{j,t}^{DA} P_{j,t}^{H} \Delta t \right) \tag{3}$$

In Eq. (3), $\min f^{DA}$ denotes the OF of the DAM clearing model; N^S denotes the set of segmented offers; $P_{m,t}^G$ denotes the capacity corresponding to the segmented offers; and π_m^G denotes the segmented offers of the generators. The constraints in the DAM clearing model include nodal power balance, branch transmission power, system power balance, and segmented capacity of the generator, of which the nodal power balance constraints are shown in Eq. (4) (Yalew et al., 2020).

$$P_{ab,t} - \sum_{k \in w_j} P_{bk,t} = P_{b,t}^{L} + P_{b,t}^{ch} - P_{b,t}^{dis} + P_{b,t}^{H} \qquad \forall b \in N_L, \forall t \in T \tag{4}$$

In Eq. (4), $P_{ab,t} - \sum_{k \in w_j} P_{bk,t}$ denotes the node power balance constraint; $P_{ab,t}$ denotes the branch transmission power, w_j denotes the set of child nodes; $P_{b,t}^{L}$ denotes the base load; N_L is the set of distribution nodes; a is the child nodes; b denotes the parent node. The branch transmission power is shown in Eq. (5).

$$-P_{ab,\max} \le P_{ab,t} \le P_{ab,\max} \qquad \forall (a,b) \in L, \forall t \in T \tag{5}$$

In Eq. (5), L denotes the set of branches; $P_{ab,\max}$ denotes the maximum transmission power of the branches. The system power balance constraint is shown in Eq. (6) (Yao et al., 2020).

$$\sum_{n \in N_{setp}} P_{m,t}^G = \sum_{b \in w_0} P_{0b,t} \qquad \forall t \in T \tag{6}$$

In Eq. (6), w_0 denotes the set of child nodes of the balancing node; and $P_{0b,t}$ denotes the branch power whose parent node is the balancing node at the t time slot. The generator capacity constraints are shown in Eq. (7) (Usman & Abdullah, 2023).

$$0 \le P_{c,t}^G \le P_c^{G,\max} N^S, \forall t \in T \tag{7}$$

In Eq. (7), $P_c^{G,\max}$ denotes the corresponding capacity of the c segment. A single load aggregator node can affect the market clearing price, but the final price is still composed by all nodes together, if it is assumed that $\lambda_{j,t}^{DA}$ is the dyadic variable of the day-ahead clearing price, then the day-ahead clearing price is the same as the $\lambda_{j,t}^{DA}$ load Eq. (8).

$$\lambda_{j,t}^{DA} = \pi_{j,t}^{DLMP,DA} \Delta t \tag{8}$$

In Eq. (8), $\pi_{j,t}^{DLMP,DA}$ denotes the day-ahead clearing tariff. Substituting Eq. (8) into Eq. (1), the load aggregator OF can be optimized in Eq. (9)

$$\min F_j^{DA} = \sum\left(\lambda_{j,t}^{DA} P_{j,t}^{H} + \lambda_{j,t}^{DA}\left(P_{j,t}^{ch} - P_{j,t}^{dis}\right)\right) \tag{9}$$

when the IES performs scheduling, the load aggregator nodes, which can be adjusted within the allowable range, the market S & D relationship at this time is shown in Fig. 1.

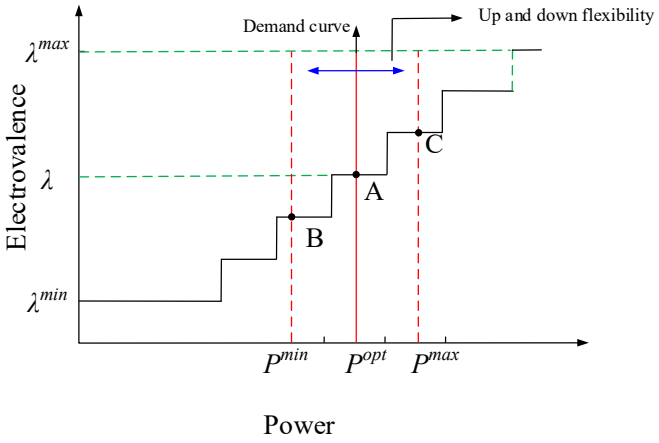


Fig. 1. Market S & D

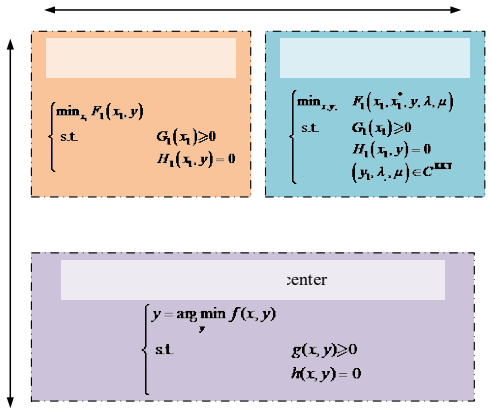


Fig. 2. Game relationships between load aggregators

Game theory is a mathematical theory that studies the strategic interactions between rational decision makers with conflicting and cooperative behaviors. The market clearing model a few days ago needs to compress the cost of power purchase, and the flexible load offer decision-making model needs to improve the efficiency of the enterprise, and there is an obvious game relationship between the two, so the study analyzes the game relationship between each load aggregator and between each node and the power trading center according to the game theory, as shown in Fig. 2. The study takes the KKT system of the market clearing problem as a node constraint, and the Stackelberg game problem can be transformed from a two-layer game to a single-layer game. When the KKT system is used as a node constraint, the coupling constraints between load aggregator nodes are also included, and constraints are formed between load aggregators because of mutual competition, and generalized Nash equilibriums are formed in the main body of the aggregators. After the Stackelberg game problem is uniquely solved, the generalized Nash equilibrium between load aggregator nodes will have multiple solutions due to the overlap between nodes' autonomous offer decisions and the fact that the Nash game problem is a linear programming problem. To address this problem, the study performs a secondary optimization calculation for the secondary optimization objective after the clearing price is quoted by the power trading center. Using the secondary optimization objective, the nodes' expected declaration success rate is monitored. At this point, the load aggregator node autonomous offer decision model is a Nash-Stackelberg equilibrium problem, and the study transforms the two-layer structure of this problem into a problem with equilibrium constrained planning for solution.

2.2 IES integrated regulation decision-making based on load response

The increase of flexible loads further adds to the intricacy of the IES, and various energy sources need to be co-scheduled during IES operation. The IES usually consists of three parts: energy input, energy conversion and energy demand. Energy input includes wind, light, and gas energy, energy conversion consists of gas turbines, fuel cells, electric boilers, refrigerants, and other equipment, and energy demand consists of various loads as indicated in Fig. 3 (Xu et al., 2021).

With the gradual depletion of non-RE sources, RE sources account for an increasing proportion of the energy supply system. However, RE units deal with instability and volatility, leading to difficulties in co-dispatch of the energy system. Integrated demand response is a rigid demand on the user side, the grid must have the ability to meet the basic demand on the user side, and the increase in flexible loads increases the difficulty of the grid for energy co-dispatch. The study constructs an IES grid structure based on the decision-making model of integrated demand response and DAM autonomous offer, as shown in Fig. 4. This IES grid has 6 nodes gas network and nodes distribution network, 4 nodes cold network nodes heat network coupling system, where the electric load includes 2 flexible load aggregation nodes. The study uses the flexible load autonomous offer decision-making model to analyze the integrated demand changes on the customer side and constructs an IES multi-objective scheduling optimization model with the integrated demand response. The multi-objective optimization model constructed by the study has three optimization objectives, and the first optimization objective is the economic efficiency of IES, which is shown in the OF in Eq. (10).

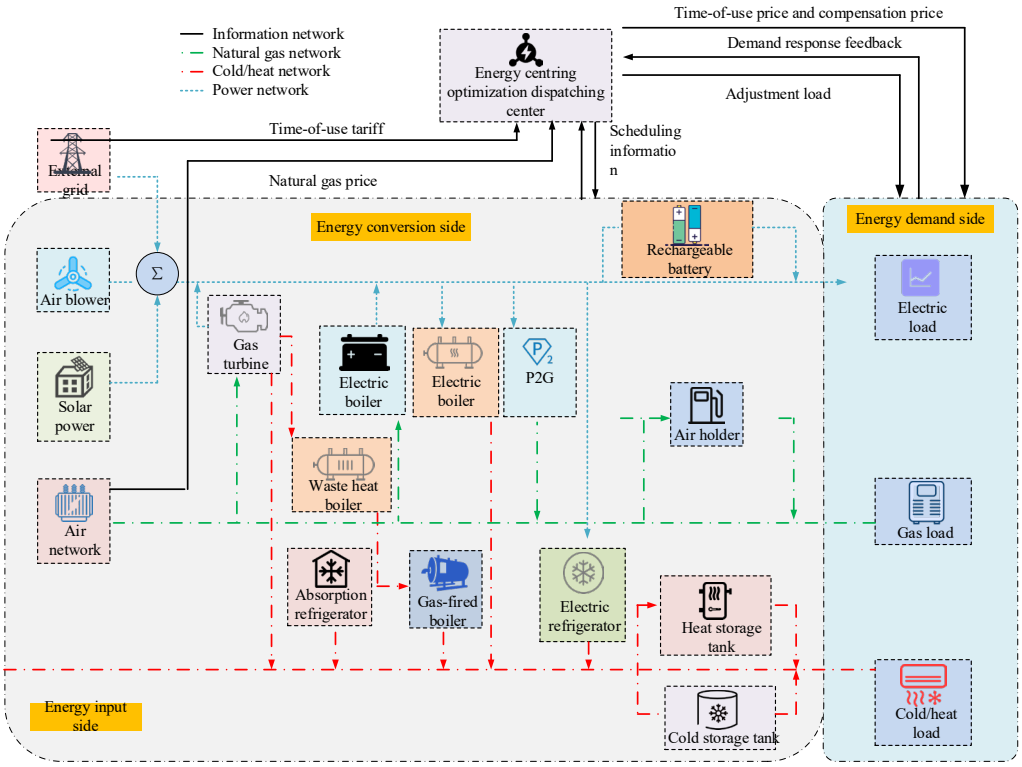


Fig. 3. Integrated energy system structure

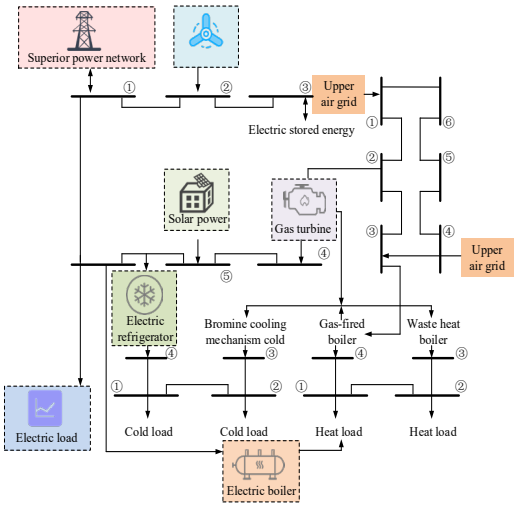


Fig. 4. Integrated energy system grid structure

$$\min F_1 = \sum_{i=1}^{n}\left(C_{i,OM} + C_{i,fule} + C_{i,AZ}\right) + C_{CCS} \tag{10}$$

In Eq. (10), F_1 denotes the total operating cost of IES; $C_{i,OM}$ denotes the O&M cost of the unit; $C_{i,fule}$ denotes the fuel consumption cost of the equipment; $C_{i,AZ}$ denotes the depreciation cost of the equipment; C_{CCS} denotes the carbon capture cost of IES; and i denotes the index of the equipment. The calculation of $C_{i,fule}$ and $C_{i,AZ}$ is shown in Eq. (11) (Zhang et al., 2021).

$$\begin{cases} C_{i,OM} = \sum_{t=1}^{T} k_{i,OM} P_i(t) \\ C_{i,fule} = c_i \Delta t \dfrac{1}{LHV} \sum_{t=1}^{T} P_i(t) \\ C_{i,AZ} = \sum_{t=1}^{T} \dfrac{k_{i,AZ}}{8760\tau_i} \dfrac{r(1+r)^{d_i}}{(1+r)^{d_i}-1} P_i(t) \end{cases} \tag{11}$$

In Eq. (11), $P_i(t)$ denotes the input power of the unit; $k_{i,OM}$ denotes the unit operating cost factor of the equipment; LHV denotes the low calorific value of natural gas; τ_i denotes the capacity factor of the equipment; $k_{i,AZ}$ denotes the upfront investment expense of the equipment per unit of capacity; c_i denotes the fuel price per unit of the equipment; d_i denotes the service life of the equipment; r denotes the stochastic parameters. The second objective is the environmental benefits of IES, and its OF is shown in Eq. (12).

$$\min F_2 = \sum_{i=1}^{g} C_i P_i(t) \tag{12}$$

In Eq. (12), F_2 denotes the environmental benefit OF; C_i denotes the treatment cost of CO2 produced by the equipment; and g denotes the number of CO2 producing equipment in the IES. The third objective is the fluctuation smoothing cost of IES, and the study introduces the expected power of the contact line road in optimizing this objective, and this objective optimization function is shown in Eq. (13).

$$\min F_3 = C_{ex,e} + C_{ex,\sigma^2} \tag{13}$$

In Eq. (13), F_3 denotes the fluctuation cost OF; $C_{ex,e}$ denotes the expected power overrun cost of the contact line; C_{ex,σ^2} denotes the power fluctuation amplitude cost. The calculation of $C_{ex,e}$ is shown in Eq. (14).

$$C_{ex,e} = \begin{cases} \gamma_1 \sum \left(\left| P_{exgrid}(t) \right| - E\left| P_{exgrid} \right| \right) & \left| P_{exgrid}(t) \right| \geq E\left| P_{exgrid} \right| \\ 0 \quad \left| P_{exgrid}(t) \right| < E\left| P_{exgrid} \right| \end{cases} \tag{14}$$

In Eq. (14), γ_1 denotes the influence factor; $P_{exgrid}(t)$ denotes the power on the contact line; and $E\left|P_{exgrid}\right|$ denotes the contact line power expectation. The calculation of C_{ex,σ^2} is shown in Eq. (15).

$$C_{ex,\sigma^2} = \gamma_2 \frac{1}{T} \sum_{t=1}^{T} \left(\left| P_{exgrid}(t) \right| - E\left| P_{exgrid} \right| \right)^2 \tag{15}$$

The study uses linear weighting to simplify the IES multi-objective optimization to single-objective optimization, and the converted OF is denoted in Eq. (16).

$$\begin{cases} F = \min \sum_{i=1}^{n} \omega_i f_i \\ \sum_{i=1}^{n} \omega_i = 1 \end{cases} \tag{16}$$

In Eq. (16), ω_i indicates the weighting coefficient. The determination of the weight coefficients is more important, and the study determines the weights of the indicators by means of autonomous screening by decision makers.

3. Experimental analysis of IES integrated regulation decision-making considering dynamic changes in electricity prices

The study constructs a flexible load-based autonomous offer decision model for the DAM and optimizes the IES co-dispatch based on this model. The study simulates and analyzes the DAM autonomous offer decision-making model and the IES co-scheduling decision in Section 3.

3.1 Simulation experiment environment and parameter setting

When the study simulates and analyzes the decision-making model of autonomous offer in the market a few days ago, the flexible loads on the user side of the IES are set to be the charging loads of new energy vehicles and the HVAC loads, and the HVAC of each aggregation node is set to be 500, the new energy vehicles of the first node is set to be 400, and the number of new energy vehicles of the second node is set to be 600. The HVAC parameters are established as denoted in Table 1.

Table 1
HVAC parameter setting

Name	Unit	Value	Name	Unit	Value
Equivalent heat capacity	kWh/°C	3.75±0.04	Equivalent thermal resistance	°C/kW	4.00±0.04
Energy efficiency ratio	/	3	Rated power	kW	3.5
Lower limit of room temperature	°C	19	Upper limit of room temperature	°C	25

The study categorizes new energy vehicles into 6:00 p.m. of the day to 8:00 a.m. of the next day, 9:00 p.m. of the day to 7:00 a.m. of the next day, and 7:00 a.m. of the day to 5:00 p.m. of the next day, according to the grid connection time. The study has set up two scenarios of co-regulation and autonomous regulation in simulating and analyzing the DAM autonomous offer decision-making model, which analyzes the day-ahead load profile, day-ahead energy plan, clearing tariffs, and nodal day-ahead clearing results. Based on the experimental environment, the study builds a simulation test environment for the DAM autonomous offer decision-making model, and the specific environmental setting is denoted in Table 2.

Table 2
Simulation of the experimental environment setting

Hardware configuration		Software configuration	
CPU	Intel Core i9-10900K	Operating system	Windows 10 Professional
GPUs	NVIDIA GeForce RTX 3080	Data processing and simulation	Python 3.8
RAM	Corsair Vengeance LPX 32GB (2 × 16GB) DDR4 3200	Programming environment	MATLAB R2021a
Storage device	Samsung 970 EVO Plus 1TB NVMe M.2 Internal SSD	/	/

In analyzing the IES integrated regulation decisions, the study analyzed the IES electric load response demand and cooling load response demand, and based on the response demand, the IES optimal operation plan was developed.

3.2 Simulation analysis of autonomous decision-making model for the DAM

To analyze the strategic ability of flexible loads in the DAM autonomous offer decision, the study analyzes the distribution network load profiles, market clearing tariffs, and flexible load energy use plans under different regulation modes. The results of day-ahead load profiles under various modes are presented in Fig. 5.

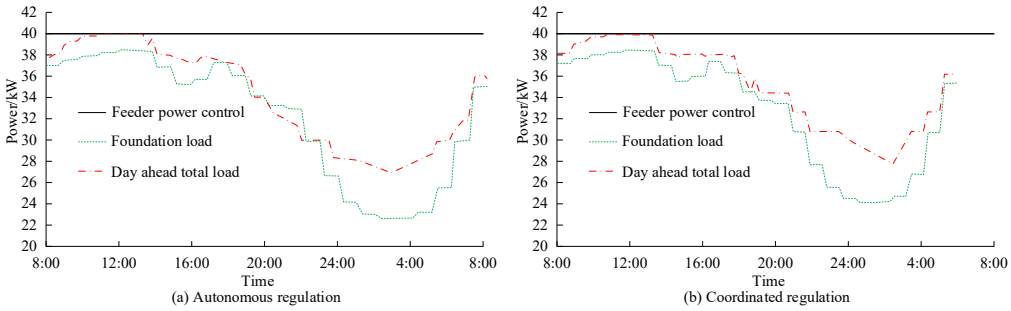


Fig. 5. Day-ahead load curves in different modes

Fig. 5(a) shows the curve of the day-ahead load in the autonomous regulation mode, which is consistently high and stays around 36 kW between 8 a.m. and 6 p.m. The day-ahead load is always high and stays around 36 kW. The day-ahead load drops to its lowest level between 12:00 pm and 4:00 am and then starts to climb gradually. Fig. 5(b) shows the curve of the day-ahead load under the co-regulation mode, and the overall trend of the curve is basically consistent with the trend of the qualification regulation, but the period of time when the day-ahead load is at a high level under the co-regulation mode is extended backward by about 2 hours. People are in a high level active state during the day, and the responding electricity load will also continue to be in a high level state. The flexible load day-ahead energy plan and outgoing tariff are shown in Fig. 6.

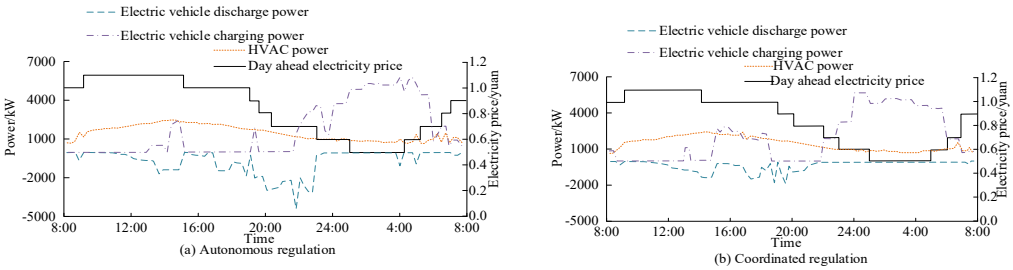


Fig. 6. Different modes of the pre-day energy plan rain clear electricity price

Fig. 6 (a) Flexible load day-ahead energy use plan and discharge tariff in autonomous regulation mode. The grid charging load of new energy vehicles is concentrated from 10:00 p.m. to 5:00 a.m. the next day, with a maximum load of about 6,000kW, and the discharging load is concentrated from 12:00 p.m. to 10:00 p.m., with a maximum load of about 4,000kW. HVAC is in an all-day load condition with a maximum load of about 2,500kW. The day-ahead electricity price is at a higher level during the daytime hours and can reach more than $1.1. Fig. 6(b) shows the day-ahead energy plan and outgoing tariff for flexible loads in the co-regulation mode. The day-ahead energy plan and outgoing tariff of day-ahead flexible loads are basically the same in different modes. Although the regulation modes are different, the total IES load remains unchanged, so the day-ahead energy plan and the outgoing tariff are basically the same. The DAM clearing results for node 1 and node 2 are shown in Fig. 7.

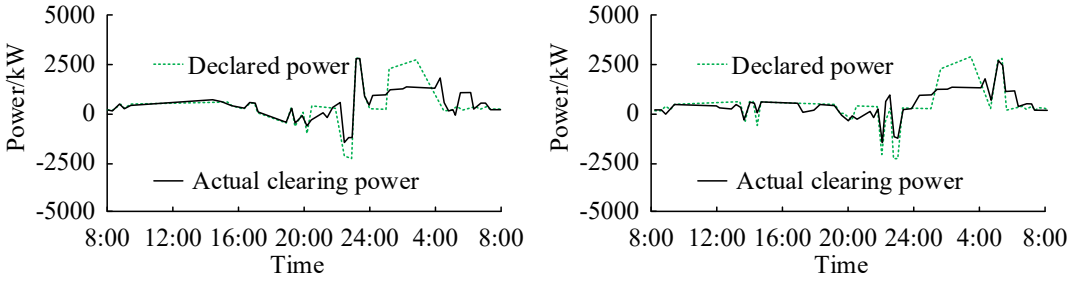


Fig. 7. The recent market clearing result of node 1 and node 2

Fig. 7(a) shows the DAM clearing results for node 1. Before 8:00 p.m., the node's actual clearing power is basically the same as the node's declared power with minimal fluctuation. From 1:00 a.m. to 4:00 a.m., the node's declared power is much higher than the ground's actual clearing power. During this period the node declared power is at 2500kW and the actual clearing power of the node is around 1500kW. Fig. 7(b) shows the DAM clearing results for node 2. Before 12:00 p.m., the node's actual clearing power fits the node's declared power better, but it is slightly lower than the fitting effect of node 1. Node 2's declared power between 1:00 a.m. and 4:00 a.m. is also much higher than the actual clearing power. From 1:00 a.m. to 4:00 a.m., most of the new energy vehicles start charging, which increases the charging load more, leading to the higher declared power of the node in this time period. However, the node's actual clearing power also needs to take into account the changes in other loads, so the node's actual clearing power is at a lower level.

3.3 IES integrated regulation decision analysis

The analysis of the integrated demand of IES can effectively understand the co-dispatch demand of IES, and the study, when optimizing the co-dispatch decision of IES, firstly analyzes the optimal operation plan of the IES power supply system and the refrigeration system, and secondly analyzes the impact of the number of loads on the operation of IES after taking into consideration of the integrated demand response, and finally, based on the integrated demand response, the optimal operation plans of the IES power supply system and the refrigeration system are optimized as shown in Fig. 8. The optimal operation plan of IES power supply system and cooling system is shown in Fig. 8.

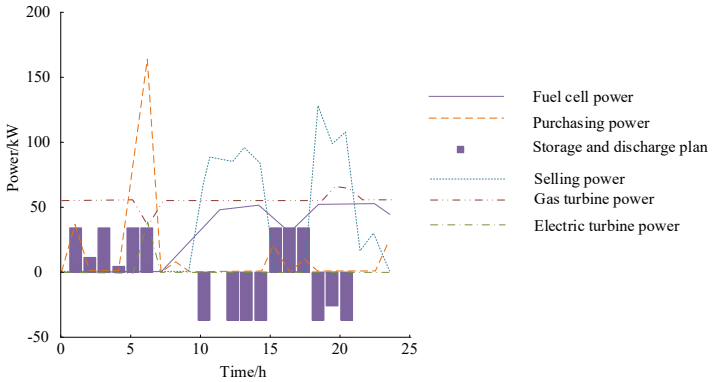


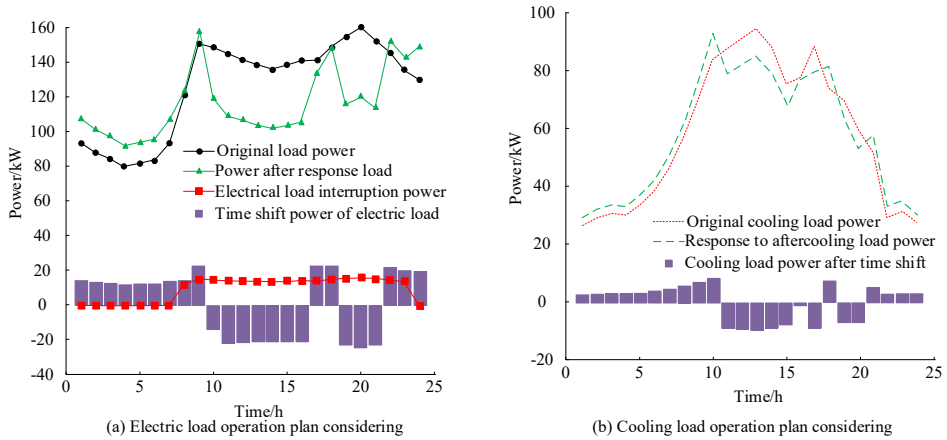
Fig. 8. Optimal operation plan of the IES power supply system and the refrigeration system

Purchased power peaked at around 160kW and sold power peaked at around 130kWh, while gas turbine power was smoother, with most of the output remaining at around 53kW. Fuel cells started to gradually increase their output power after 10am. The storage and discharge program stores power at higher power sales and discharges power at higher power purchases. The effect of the number of loads on the operating cost of the IES is denoted in Table 3.

Table 3
Effect of load quantity on IES operation

Scene	Fluctuating cost (yuan)	Carbon emissions costs (yuan)	Carbon emissions (kg)	Operating cost (yuan)	Total cost (yuan)
1	756.22	394.70	1062.17	2046.22	2802.44
2	784.11	394.70	1062.17	1953.76	2737.87
3	765.25	381.83	1032.76	1953.49	2718.74
4	749.88	381.83	1032.76	1878.89	2628.77
5	763.36	381.83	1032.76	1857.74	2618.10

Scenario 1 to Scenario 5 in Table 3, the considered load cases are gradually increasing. The system operating cost, carbon emission cost, total cost and carbon emission are gradually decreasing as the considered loads are increasing, but the fluctuating cost of IES increases as the loads increase. The operational power purchase plan of the IES power supply system and the load operation plan of the cooling system after considering the integrated demand response are shown in Fig. 9.



(a) Electric load operation plan considering comprehensive demand response

(b) Cooling load operation plan considering comprehensive demand response

Fig. 9. Electrical load and cooling load optimization of IES after considering comprehensive demand response

Fig. 9(a) shows the comparison of the electric load operation plan after considering the integrated demand response. When the interruption of the flexible load occurs, the grid's post-response load power drops significantly. After the occurrence of electric load time shift, the load power after grid response also drops rapidly. Fig. 9(b) shows the comparison of the cold load operation plan after considering the integrated demand response. There is a small fluctuation in the cold load power after the IES response to the cold load change. The highest original cold load is about 95kW.After the response, the highest cold load is still about 95kW but the peak of the cold load appears to be shifted forward.

4. Conclusion

In order to optimize the IES regulation strategy and optimize the IES operation plan, the study considers the flexible load demand on the customer side, establishes a DAM autonomous offer decision model, and analyzes the difference between the day-ahead clearing tariff and the node declaration. And the difference between the day-ahead clearing tariff and the node-declared price, the IES is optimized for multi-objective regulation decision-making with economic benefit, environmental benefit and fluctuation cost. The results show that the day-ahead load is always at a high level between 8 am and 6 pm. The grid charging load of new energy vehicles is concentrated between 10 p.m. and 5 a.m. the next day, with a maximum load of about 6000 kW, and the discharging load is concentrated between 12 noon and 10 p.m., with a maximum load of about 4000 kW. Before 8 p.m., the actual discharging power of the node is basically consistent with the declared power of the node, and the fluctuation is extremely small. As the considered load continues to increase, the system operating cost, carbon emission cost, total cost and carbon emission are gradually decreasing. After considering the integrated response demand, the power out of the IES power load between 10:00 am and 3:00 pm can be reduced in advance to minimize the fluctuation of IES operation. The study optimizes and analyzes the IES energy pre-dispatch decision by means of an autonomous offer decision model in the market a few days ago, which improves the IES operation stability and reduces the IES operation cost. However, the study takes less consideration of the heat supply system and gas supply system when analyzing the IES load, and will further analyze the IES heat supply system and gas supply system load in the future.

Acknowledgment

The work was financially supported by Science and Technology Projects from State Grid Corporation of China (Research and demonstration of multi-time scale operation optimization technology of urban regional integrated energy systems under electricity spot market, No.: 5400-202417200A-1-1-ZN).

Data Availability Statement

The data that support the findings of the study are available from the corresponding author upon reasonable request.

References

Ameur, H.B., Ftiti, Z., & Louhichi, W. (2022). Revisiting the relationship between spot and futures markets: Evidence from commodity markets and NARDL framework. *Annals of Operations Research*, *313*(1), 171-189.

Azuatalam, D., Chapman, A.C., & Verbič, G. (2020). Probabilistic assessment of impact of flexible loads under network tariffs in low-voltage distribution networks. *Journal of Modern Power Systems and Clean Energy*, *9*(4), 951-962.

Basit, M.A., Dilshad, S., Badar, R., & Sami ur Rehman, S.M. (2020). Limitations, challenges, and solution approaches in grid-connected renewable energy systems. *International Journal of Energy Research*, *44*(6), 4132-4162.

Cao, D., Hu, W., Zhao, J., Zhang, G., Zhang, B., Liu, Z., & Blaabjerg, F. (2020). Reinforcement learning and its applications in modern power and energy systems: a review. *Journal of Modern Power Systems and Clean Energy*, *8*(6), 1029-1042.

Cao, M., Shao, C., Hu, B., Xie, K., Li, W., Peng, L., & Zhang, W. (2021). Reliability assessment of integrated energy systems considering emergency dispatch based on dynamic optimal energy flow. optimal energy flow. *IEEE Transactions on Sustainable Energy*, *13*(1), 290-301.

Dierks, L., & Seuken, S. (2022). Cloud pricing: the spot market strikes back. *Management Science*, *68*(1), 105-122.

Ge, L., Li, Y., Yan, J., Wang, Y., & Zhang, N. (2021a). Short-term load prediction of integrated energy system with wavelet neural network model based on improved particle swarm optimization and chaos optimization algorithm. *Journal of Modern Power Systems and Clean Energy*, *9*(6), 1490-1499.

Ge, L., Liu, H., Yan, J., Zhu, X., Zhang, S., & Li, Y. (2021b). Optimal integrated energy system planning with DG uncertainty affine model and carbon emissions charges. *IEEE Transactions on Sustainable Energy*, *13*(2), 905-918.

Li, P., Ma, X., Chen, M., Tan, J., Yang, P., Zhao, Z., & Lai, L.L. (2022). Aggregate regulation strategy of distributed energy storage under power spot market in China. *IET Renewable Power Generation*, *16*(2), 313-328.

Li, Y., Han, M., Yang, Z., & Li, G. (2021). Coordinating flexible demand response and renewable uncertainties for scheduling of community integrated energy systems with an electric vehicle charging station: a bi-level approach. *IEEE Transactions on Sustainable Energy*, *12*(4), 2321-2331.

Li, Y., Wang, B., Yang, Z., Li, J., & Li, G. (2021). Optimal scheduling of integrated demand response-enabled community-integrated energy systems in uncertain environments. *IEEE Transactions on Industry Applications*, *58*(2), 2640-2651.

Lin, L., Huang, C., & Zhao, L. (2020). Long-term hydropower pricing in the spot market with evolutionary game theory. *Journal of Coastal Research*, *103*(SI), 117-119.

Lv, L., Wu, Z., Zhang, J., Zhang, L., Tan, Z., & Tian, Z. (2021). A VMD and LSTM based hybrid model of load forecasting for power grid security. *IEEE Transactions on Industrial Informatics*, *18*(9), 6474-6482.

Pan, G., Gu, W., Lu, Y., Qiu, H., Lu, S., & Yao, S. (2020). Optimal planning for electricity-hydrogen integrated energy system considering power to hydrogen and heat and seasonal storage. *IEEE Transactions on Sustainable Energy*, *11*(4), 2662-2676.

Perera, A.T.D., Nik, V.M., Chen, D., Scartezzini, J.L., & Hong, T. (2020). Quantifying the impacts of climate change and extreme climate events on energy systems. *Nature Energy*, *5*(2), 150-159.

Shi, M., Wang, H., Xie, P., Lyu, C., Jian, L., & Jia, Y. (2022). Distributed energy scheduling for integrated energy system clusters with peer-to-peer energy transaction. *IEEE Transactions on Smart Grid*, *14*(1), 142-156.

Sifat, I.M., Mohamad, A., & Amin, K.R. (2021). Intertemporal price discovery between stock index futures and spot markets: new evidence from high- frequency data. *International Journal of Finance & Economics*, *26*(1), 898-913.

Sun, P., Hao, X., Wang, J., Shen, D., & Tian, L. (2021). Low-carbon economic operation for integrated energy system considering carbon trading mechanism. *Energy Science & Engineering*, *9*(11), 2064-2078.

Usman, A.M., & Abdullah, M.K. (2023). An Assessment of Building Energy Consumption Characteristics Using Analytical Energy and Carbon Footprint Assessment Model. *Green and Low-Carbon Economy*, *1*(1), 28-40.

Wu, S., Lin, J., Li, J., & Song, Y. (2022). Electricity allocation strategy for on-site hydrogen refueling stations in the forward and spot markets. *IET Renewable Power Generation*, *16*(12), 2532-2546.

Xu, Z., Han, G., Liu, L., Martinez-Garcia, M., & Wang, Z. (2021). Multi-energy scheduling of an industrial integrated energy system by reinforcement learning-based differential evolution. *IEEE Transactions on Green Communications and Networking, 5*(3), 1077-1090.

Yalew, S.G., Vliet, M.T., Gernaat, D.E., Ludwig, F., Miara, A., Park, C., & Van Vuuren, D.P. (2020). Impacts of climate change on energy systems in global and regional scenarios. *Nature Energy*, *5*(10), 794-802.

Yao, S., Gu, W., Lu, S., Zhou, S., Wu, Z., Pan, G., & He, D. (2020). Dynamic optimal energy flow in the heat and electricity integrated energy system. *IEEE Transactions on Sustainable Energy*, *12*(1), 179-190.

Zhang, D., Zhu, H., Zhang, H., Goh, H.H., Liu, H., & Wu, T. (2021). Multi-objective optimization for smart integrated energy system considering demand responses and dynamic prices. *IEEE Transactions on Smart Grid*, *13*(2), 1100-1112.

Zhang, N., Sun, Q., Yang, L., Li, Y. (2021). Event-triggered distributed hybrid control scheme for the integrated energy system. *IEEE Transactions on Industrial Informatics*, *18*(2), 835-846.