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Study on low-carbon service mode of park-level integrated energy system with flexible supply and demand balance

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Against the backdrop of “carbon peaking and carbon neutrality” goals in China, the park-level integrated energy system is a significant approach to meeting the energy consumption demand of users and improving the utilization rate of new energy. To take into account both the interests of integrated energy services (IES) providers and the current power market rules in China, targeting at low-carbon energy consumption, a balancing service mode for integrated energy services providers is created herein based on the idea of balancing multiple interests of regional integrated energy services providers. It aims to break down the market barriers and address the tricky problem that the integrated energy services industry fails to establish a sophisticated industrial system under the original mode. Combining the integrated energy services with the auxiliary market of power balance, the paper analyzes the characteristics of energy flow within the system, and puts forward the optimization scheme of regional integrated energy balancing services under the low-carbon background. The objective is solved by Mayfly algorithm and compared for analysis, and the results show that the optimal daily operating cost is 2632.59 yuan and the daily carbon emission is 3869.90 kg under the typical industrial scenario. The examples provided here show that the optimization plan for integrated energy balancing services can reduce carbon emissions from the park-level integrated energy system and boost the revenue for integrated energy service providers. It provides theoretical support for the green transformation of energy enterprises and promotes the healthy development of the global integrated energy industry.

KEYWORDS

green innovation, integrated energy system services provider, balancing service, mechanism design, low-carbon transition

1 Introduction

In 2020, China proposed the“30–60”goals of carbon peaking and carbon neutrality (“Dual Carbon”), aiming at coping with the increasing global energy demand and realizing its plan of low-carbon development. In recent years, the total power consumption of China has been increasing rapidly, reaching 8.6 trillion kWh in 2022. The Chinese government is actively advancing the clean energy technology industry to establish a clean and low-carbon energy sector, ensuring a safe and efficient transformation and development. Currently, non-fossil energy power generation accounts for 50.9% of the total installed capacity in China, with new energy power generation surpassing 13% of the total. However, in terms of the new energy market, there are still some problems, such as large-scale heterogeneity of market players, high market operating costs, and uneven transmission and distribution of new energy, leading to the inability of private capital to connect the new energy resources with the current power market. To accomplish the objective of utilizing clean and efficient energy effectively, it is imperative to make breakthroughs that can overcome obstacles in the present new energy market and drive the transition of the energy structure (Li and Lin, 2017).

The electricity-centered integrated energy system is a crucial measure to improve the regulation ability of new energy generation and promote green innovation and development of the industry (Collins et al., 2017; Sun et al., 2022). Under the Dual Carbon goals, small and medium-sized energy enterprises in China have to consider both the affordability of clean energy and the extra costs caused by excessive carbon emissions. Integrated Energy Services is exactly an effective solution for enterprises to meet the above challenges. It enables new energy companies to enter the market without disrupting the traditional power market equilibrium, while also facilitating the integration of a substantial amount of new energy into the supply and consumption systems, making it a vital means of achieving the Dual Carbon goals. Essentially, the integrated energy system is a novel energy system created through the merging and streamlining of production, transmission, distribution, and delivery processes of different energy sources during overall planning, construction, and operation (Mohammadi et al., 2017). At present, the research on the technologies of integrating energy sources such as electricity, heat and gas within the system are relatively mature (Ghosh and Dincer, 2014). How to address the environmental pollution by designing the integrated energy system has become the focus of scholars' research in recent years. Literature (Li et al., 2018; Wang et al., 2019; Chen and Wang, 2020) mainly deals with the overall optimization of the integrated energy system, starting with allocation of resources within the system and aiming to reduce the operating cost of investors by means of establishing optimization models and so forth. However, focusing solely on optimizing a single internal feature of the system without considering the market behavior of service providers will hinder the advancement of integrated energy system implementation. With this information, numerous scholars have initiated studies on the correlation between supply and demand in the integrated energy system, aiming to ascertain a harmonious equilibrium among investors, the power grid, and users. Game theory can better analyze the income relationship among the energy market players and accurately describe the interaction among them (He et al., 2020). Literature (Li et al., 2021; Li et al., 2022; Wang et al., 2022; Zhang et al., 2022; Lu et al., 2023) analyzes the interest-based relationship between IES providers and power enterprises by establishing a game model, aiming at improving the interaction rules of energy market players and enhancing the economy and stability of the integrated energy system.

The research on the integrated energy service market in developed countries is much earlier, mainly the theoretical research on the combination of market and new energy services. As a major energy producer and consumer, the United States is committed to establishing an independent energy system with the most diversified power supply system in the world (Huntington et al., 2020; Tsai et al., 2020). Although policies vary in different states, they basically stipulate that the real-time power market should promote the optimal operation of the new energy market. Literature (Verzijlbergh et al., 2017) discusses the challenges and countermeasures after the large-scale entry of clean energy into the power system in European countries. From the above literature, it can be concluded that the development of renewable energy and related systems and mechanisms are interdependent, thus energy trade and policy coordination will gradually become unified globally. On this basis, many Chinese scholars have made attempts to build an integrated energy services market system adapted to China's national conditions by referring to the experience of developed countries (Wang et al., 2015). Literature (Lin and Purra, 2019) emphasizes the establishment of power regulators, which contributes to the transition from traditional power market to new energy market. Literature (Pang et al., 2019) designs a multi-platform electricity sales model based on investment analysis to promote new energy consumption within the region and improve environmental quality. Literature (Hu et al., 2021) engineers an auxiliary service mechanism for renewable energy power generation to push forward the consumption of new energy power generation. Literature (Gu et al., 2020) establishes the price optimization model of the integrated energy system to obtain the intra-day optimal scheduling scheme for service providers. At present, many Chinese scholars have studied the theory of integrated energy market system in line with China's national conditions, with their achievements mainly including optimal bidding, market clearing, and unified optimization. This overall optimization system is feasible, though it is too idealistic for service providers, as there are several problems. First, the cost of reform is not affordable for energy service providers, with excessively high investment risks. Second, the market clearing mode is so complicated that service providers are still subject to their higher-level power grid.

Starting with the above problems, this study designs to improve the balancing service mechanism of the regional integrated energy services without any disruptive reform on the existing power market structure. The service mechanism can ensure the balance between power generation and consumption in a small scale, achieve collaborative operation among all players under the limited scheduling mode, and avoid risks in the complex market. Following the green and low carbon principle and learning from the mature integrated energy market mechanism of developed countries, an innovative balancing service mode for IES providers is designed. According to the characteristics of park-level integrated energy system, the short-term balancing service optimization scheme for regional IES providers is put forward. In comparison to current research theories, its unique aspect is the integration of balancing services and integrated energy services. This can improve the value of service providers by lowering integrated energy consumption, saving additional energy consumption quotas, and reducing the extra costs from information asymmetry. The integrated energy system's small-scale energy dispatch can be achieved by IES providers, enabling improved service to China's emerging power market and facilitating the shift towards a unified national power market system in the future.

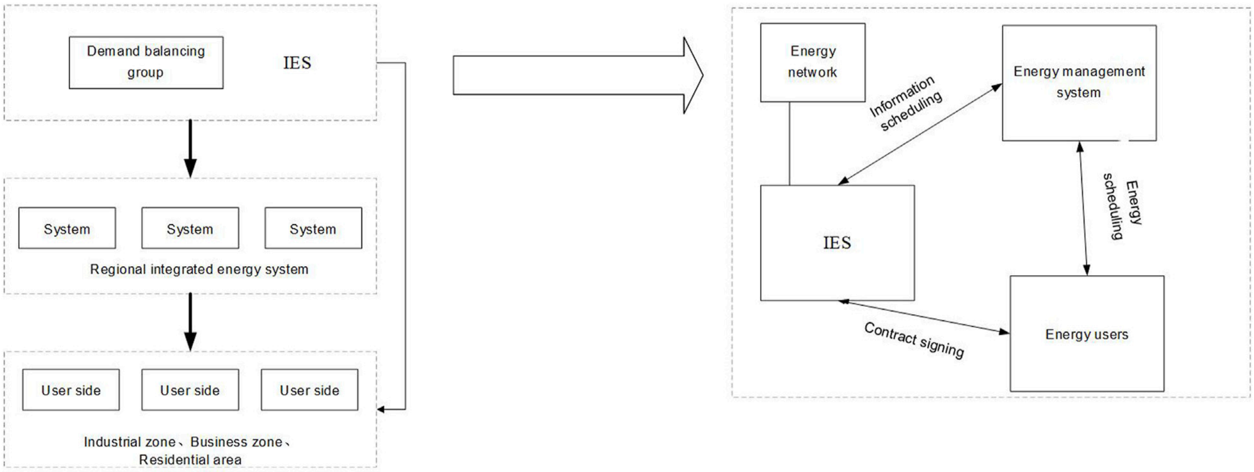

FIGURE 1
Balancing group mode.

2 IES balancing service mode

2.1 Overview

For the last few years, the integrated energy system at the regional level in China has become relatively mature in terms of technology, with several demonstration projects already achieving phased results (Liu et al., 2018). However, widespread adoption of the integrated energy system remains challenging. China's new power market is still in its infancy, with insufficient basic data of power grid, electricity production of power producers, power load of users, etc. If service providers enter the market recklessly, their energy utilization rate may decline due to information asymmetry. As a result, they will be unable to optimize the allocation of resources, and have to cope with problems such as complicated income and diversified players. The interest-based relationship between the power generation side and the power transmission side has no common ground, which leads to low absorption in the new energy market and lack of motivation of service providers (Zhang et al., 2016).

Regional IES providers, as organizations that meet the diverse energy production and consumption demand of customers, are responsible for the construction of integrated energy systems in multiple parks (Morley, 2018). It is difficult for the integrated energy system to adapt to the unified service management mode of the major power grid. Service providers can achieve energy adjustments through the signing of service contracts. Even a slight deviation will lead to disruptive reforms of service providers. However, on a small scale, different parks that have quite close capacity levels in respect of integrated energy system are able to independently provide energy services. Service providers can realize energy adjustments by signing service contracts. Based on the above factors, combined with the current system and mechanism of China's power market, it is more reasonable to choose the "balancing group" service mechanism: several integrated energy systems make up a "capacity balancing group", and service providers and scheduling systems constitute a "demand balancing group". It will enable service providers to gain adjustment ability through energy interconnection among lower-level systems and break away from their reliance on the major power grid.

As can be seen from the above Figure 1, the IES provider co-ordinates the generation, distribution and sales of energy in the park. After signing service contracts with the service providers, the park can utilize the supply and demand scheme from the integrated energy system in the region. Since balancing services are uniformly distributed by service providers, the balancing service mode within the region can reduce the risks of assessment deviation.

2.2 Scheduling center

The user-side energy consumption of park-level integrated energy system has diversified sources, with high requirements on the safety of energy production and transmission, thus the scheduling center plays an important role therein. The integrated energy system's energy structure is characterized by integrity, proximity, and interaction. The means such as scheduling operation, supervision organization and information disclosure based on the traditional power grid is unable to match with the internal energy circulation characteristics of the system. Information interaction on a larger scale will lead to higher risk of information asymmetry, thus increasing the transaction cost of service providers. The scheduling center can narrow the information dimension, directly connect the power grid with the integrated energy system, and guarantee the operation of generating units within the system and the energy demand of users through monitoring. The implementation process is relatively easy, with low construction cost on a small scale, which can address the problem of high investment risk when service providers make decisions.

The service providers launch the balancing service through the data given by the scheduling organization, and obtain functions such as unit peak regulation and optimization of transmission and distribution constraints. The scheduling organization is shown in Figure 2.

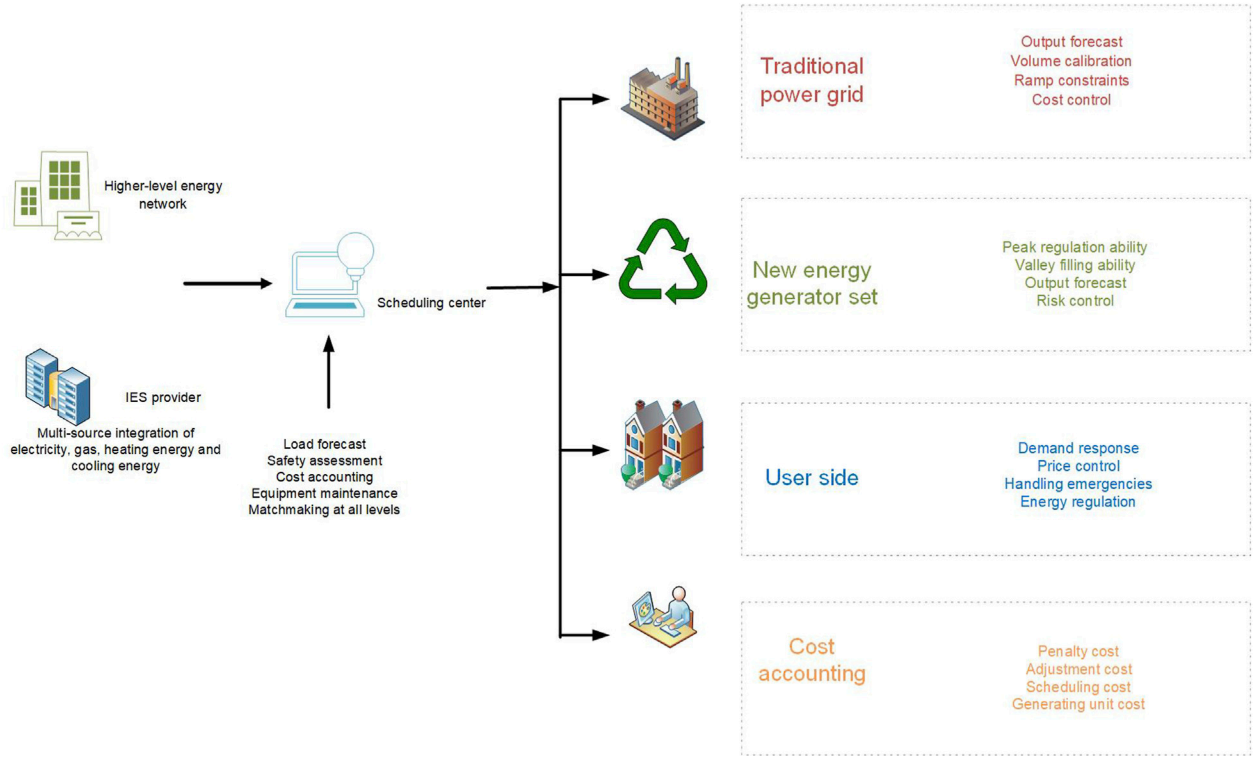

FIGURE 2
Schematic diagram of the scheduling center.

TABLE 1 Schematic table of intra-day window periods.

Time	Window Periods
0: 00–8: 00	Optional window
8: 00–15: 00	Available window
15: 00–18: 00	Optional window
18: 00–21: 00	Available window
21: 00–0: 00	Optional window

2.3 Design of the balancing service mechanism

At present, mechanisms related to participants in the auxiliary market, energy providers and transaction details in China still need to be improved, and the conditions for implementing long-term auxiliary services are not sufficient. It is essential to draw lessons from the experienced markets of developed nations. The combination of charging standard, scheduling method and supervision mode in short-term balancing service mechanism with the park-level integrated energy system can meet the needs of service providers (Liu et al., 2022). The capacity of the park-level integrated energy system is uncertain, and there are deviations in terms of energy demand forecast and new energy power generation to some extent. In order to ensure the stable energy consumption of users in the region and the smooth operation of the higher-level power grid, it is more reasonable to adopt a highly flexible short-term standby balancing service mechanism.

The short-term standby balancing service mechanism has two available windows during the day, which are referred to as available windows. The Schematic table of intra-day window periods can be shown in Table 1. When the service providers deliver energy close to the beginning and end of the available window, it is necessary to make a smooth transition between the balancing service energy and the energy specified in the contract. Therefore, the periods with state changes during the day include pre-window period and post-window period. Upon receiving instructions from the scheduling center, the service providers will align the power level from the balancing service level to the contracted level during the pre-window period, and *vice versa* in the post-window period.

2.4 Settlement of service expenses

Presently, the power market in China has no compensation mechanism for balancing services, and tends to ignore the characteristics of different types of generating units when developing the expense settlement rules. The short-term balancing service mechanism features a clear service expense settlement structure and strong timeliness, which meets the conditions for IES providers to enter the balancing market. The settlement formulas of available expenses, use expenses, adjustment expenses and penalty expenses are as follows.

2.4.1 Settlement of available expenses

$$C_{A,m} = \sum max\left(C_{A,j}, 0\right)$$
$$C_{A,j} = 0.5\left(\sum P_{A,j}.\alpha_1.\alpha_{2-} \sum P_{A,j}.\alpha_3\right)$$

$C_{A,m}$ is the available expenses for service providers, and $P_{A,j}$ is the power under the contract. $\alpha_1, \alpha_2, \alpha_3$ are indicator variable. α_1 indicates that the available expense is 0 when it is not available during the settlement period.In the opposite case, take 1. α_2 indicates that during the trial period, force majeure causes the available expense to be unavailable in case of 0, In the opposite case, take 1. α_3 indicates that the available expense is 0 when it cannot be used due to the system's own problems. In the opposite case, take 1.

2.4.2 Settlement of use expenses

This price reflects whether the available capacity of each unit in the integrated energy system is sufficient. Once the gap between the available power output and the required power output gets wider, the use price will increase, and *vice versa*. In the process of studying the use expenses, the loss of load probability (LOLP) P_L is an important indicator measuring the reliability of power supply in each settlement period. It refers to the probability that the power supply is insufficient to meet the capacity requirements for a given system supply and demand level, with a value range of (0, 1). The expense settlement formula is as follows:

$$M_j = X_{j-}U_{j-}P_{r,j}$$
$$P_{r,s} = D_s + P_{e,s} + R_{l,s} - P_{n,s}$$
$$R_{l,s} = \frac{L_j - 0.01D_j}{\mu_1\mu_2}$$

M_j is the unit safety margin, X_j is the total output of traditional generating units, U_j is the predicted total output value of new energy generating units, $P_{e,s}$ is active power synthesis, $P_{r,j}$ is the integrated settlement of auxiliary services, D_j is the predicted total demand for electricity during the settlement period, and $P_{n,s}$ is the reserve capacity provided by auxiliary services. $\mu_{1,}\mu_2$ refer to the response retention factor and the rise response standby factor.

2.4.3 Settlement of adjustment expenses

The adjustment expenses consist of the working times, scheduling power and available expenses in the current month of each capacity balancing group. The formula is as follows:

$$C_{s,n} = \frac{\alpha\left(1 - \beta_n\right)\sum_{i=0}^{n} C_{A,m} \min\left(F_n, M_n\right)}{F_n}$$

$C_{s,n}$ is the adjustment expenses of the month, M_n is the times of providing standby services by the system, α is regulatory factor, β_n is the delivery rate of unit capacity that the system can provide, and F_n is the reference value of the times of providing service in the current month, taking 3.

2.4.4 Settlement of penalty expenses

If the system fails to meet the capacity delivery rate under the contract after the service provider has signed the service contract, then the service provider will pay extra adjustment expenses to turn to the higher-level energy network for supplement. The formula for settlement of expenses is as follows:

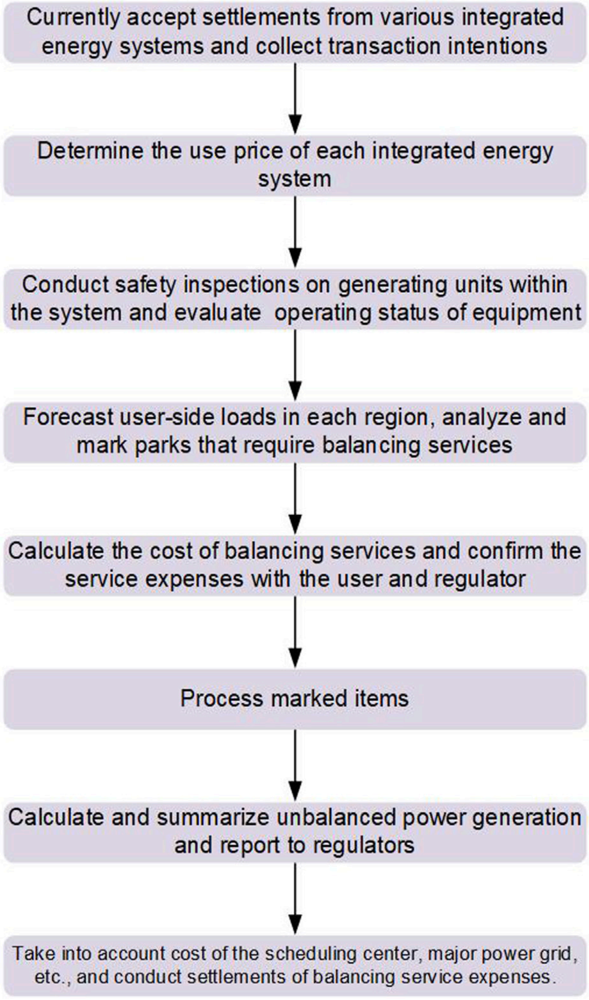

FIGURE 3
Flow chart of balancing services.

$$C_n = \frac{\sum_{i=0}^{n} P_{m,s}}{\sum_{i=0}^{n} P_{E,s} + \sum_{i=0}^{n} P_{r,s}}$$

C_n is the additional adjustment expenses, $\sum_{i=0}^{n} P_{m,s}$ is the unit capacity that can be put into use under the contract, $\sum_{i=0}^{n} P_{E,j}$ is the unit capacity that can be delivered during the service period, and $\sum_{i=0}^{n} P_{r,s}$ is the unit capacity that cannot be provided during the service period.

2.5 Operation optimization model

The predicted fluctuations and deviations can be easily found during the operation of the integrated energy system, thus service providers need to determine the day-ahead use prices of all systems in the region, and carry out strict safety inspection and balance expenses calculation. This balancing services can be illustrated in Figure 3.

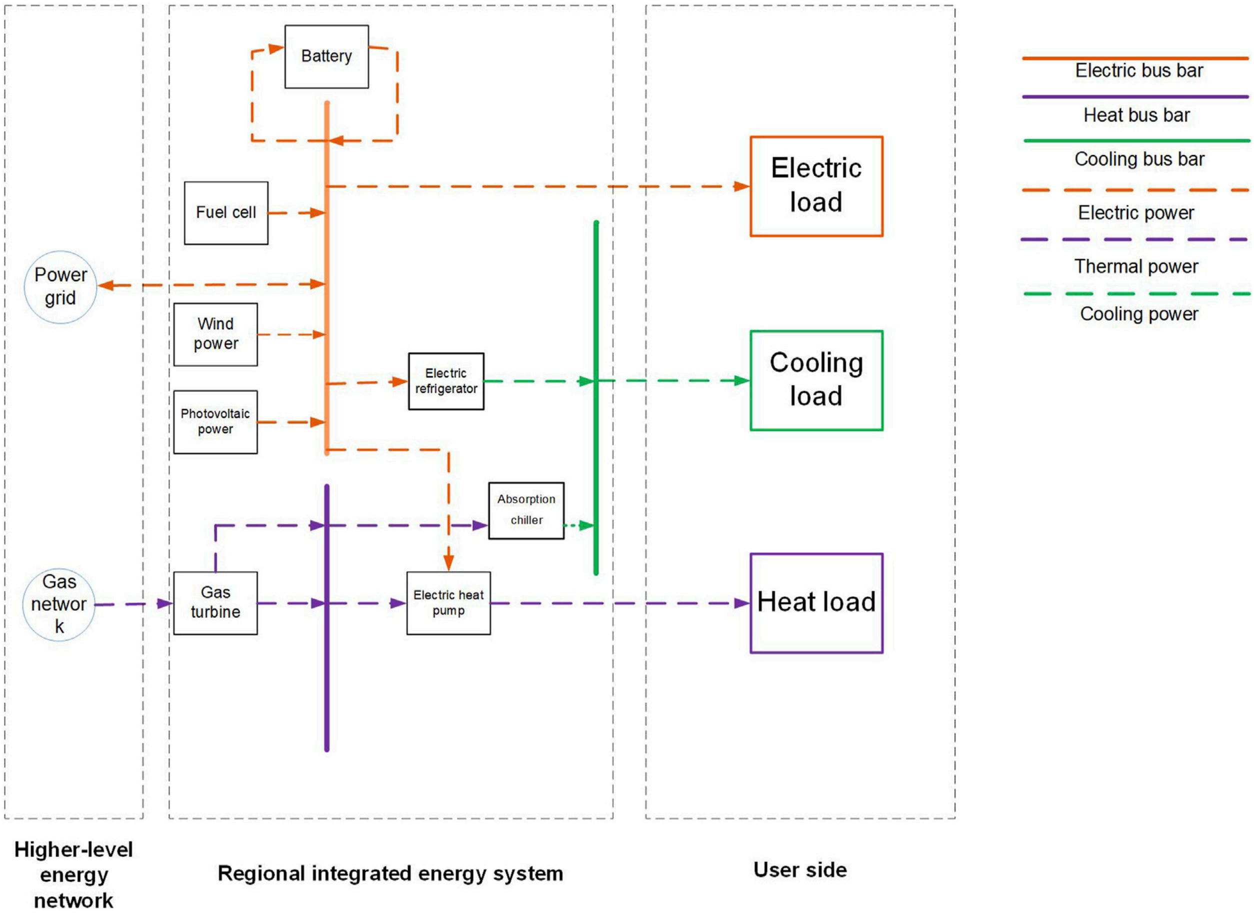

FIGURE 4
Structure diagram of the park-level integrated energy system.

The major energy consumption environment of the park-level integrated energy system still features self-sufficiency, so if the service provider can faithfully perform the contract, it will be unlikely to cause great fluctuations in the electricity prices of the major power grid. As the intra-day forecast technologies of the integrated energy system are mature with accurate results, the paper focuses on the intra-day service of the service provider, taking the power curve of the user side within 24 h as the reference standard for research. In order to make the optimization model easier, the paper assumes that the real-time electricity price is equal to the clearing electricity price. According to the ultra-short-term forecast of load and distributed generation power, aiming at the lowest integrated energy consumption cost, the deviation of the day-ahead plan is corrected, so as to realize the coordination between the intra-day system plan and the real-time phased local optimization.

3 Modeling of the integrated energy system

3.1 System overview

Compared with the traditional energy structure, the park-level integrated energy system has more uncertainties, complex characteristics and multiple time scales. Its scenario construction and prediction are more complicated than those of the traditional power system with thermal power as the core. The park-level integrated energy system includes micro gas turbines, photovoltaic panels, wind power generators, electric heat pumps and electric refrigerators. The service provider is responsible for building an integrated energy system within the park. The structure diagram of the park-level integrated energy system is illustrated in Figure 4.

3.2 System model

3.2.1 Photovoltaic cell (PV)

PV cell is a kind of widely-used renewable energy power generation device. Its voltage in the power generation process is in a nonlinear state, and the power generation formula is as follows:

$$P_{pv}^{t} = P_{stc}\frac{G_c}{G_{stc}}\left[1 + K\left(T_c - T_{stc}\right)\right]$$

P_{stc} is the output power under standard test conditions, G_c is the illumination intensity, G_{stc} is the standard illumination intensity, K is the PV power generation coefficient, T_c is the panel temperature, and T_{stc} is the temperature under test conditions.

The output cost formula of PV cells is as follows:

$$C^t_{pv} = \rho_{pv} P^t_{pv} + C_1 P^{tf}_{pv} e^{pv}$$

ρ_{pv} is the cost coefficient of PV power generation, C_1 is the penalty coefficient of PV cells, and e^{pv} is the prediction error parameter representing the uncertainty of PV cell output.

3.2.2 Wind turbine (WT)

The WT collects wind energy through the blades of the turbine prior to transmitting it to the generator for power generation. The generation power varies with the wind velocity. Wind velocity can be divided into three types: gust velocity, average wind velocity and random wind velocity. The average wind velocity V_{as} is studied herein. The power generation formula is as follows:

$$P_{wt} = a {V_{as}}^3 - b P_r$$

$$a = \frac{P_r}{{V_r}^3 - {V_{as}}^3} \quad b = \frac{{V_{as}}^3}{{V_r}^3 - {V_{as}}^3}$$

P_r is the rated power of the wind turbine and V_r is the rated wind velocity.

The output cost formula of wind turbine is as follows:

$$C^t_{wt} = \rho_{wt} P^t_{wt} + C_2 P^{tf}_{wt} e^{wt}$$

ρ_{wt} is the cost coefficient of wind power generation, C_2 is the penalty coefficient of wind turbine, and e^{wt} is the prediction error parameter representing the uncertainty of WT output.

3.2.3 Fuel cell (FC)

FC converts chemical energy into electric energy, therefore it is also known as electrochemical generator, which can reduce the limitation of Carnot Cycle effect, with high efficiency, good environmental performance and long service life. The formula of its power generation cost is as follows:

$$C_{FC} = C_{nl} \frac{1}{LHV_f} \sum_n \frac{\mu_{FC}}{P_{FC}}$$

C_{nl} is the price of natural gas, LHV_f is the low calorific value of natural gas, μ_{FC} is the net transmission power, P_{FC} is the total efficiency of FCs.

3.2.4 Microturbine (MT)

MT converting gas energy or biogas energy into heat energy and electric energy is an important energy conversion device in the integrated energy system. After natural gas is input into the turbine unit of MT, electric energy is generated by the generator. When the temperature is low, the discharged gas can be converted into cooling energy and heat energy through the lithium bromide unit. The cooling energy output is linked to an absorption chiller in order to supply cooling to the user's side. The formula for its power generation is analogous to that of a quadratic function:

$$H^t_{MT} = \alpha p^t_{MT} 2 + \beta p^t_{MT} + \gamma$$

p^t_{MT} is the generation power of MT, H^t_{MT} is the waste heat of gas turbine, and α, β, γ are the waste heat coefficients of gas turbine. The heat generation and refrigeration formulas of gas turbine using waste heat are as follows:

$$P_{ho} = H^t_{MT} cop_{ho} \delta_{rec}$$

$$P_{co} = H^t_{MT} cop_{co} \delta_{rec}$$

P_{ho} and P_{co} refer to heat generation power and refrigeration power, cop_{ho} and cop_{co} indicate the heating coefficient and cooling coefficient, and δ_{rec} is the waste heat recovery power.

The cost coefficient of MT can be approximate to the gas cost that it needs, and the formula is similar to a linear function:

$$C_{MT} = a P^t_{MT} + b$$

a and b are the cost coefficients of MT.

3.2.5 Electric heat pump (HP)

Electric HP has become an important technical device in new houses in developed countries, and its low carbon emission meets the requirement of the integrated energy system. The energy efficiency ratio of electric HP (heat generated by equipment divided by electric energy consumed by heating) and thermal power are the key parameters of the generating unit. Its heat production formula is as follows:

$$H^t_{HP} = COP_{HT} P^t_{HP}$$

H^t_{HP} is the heat output per unit time of the electric HP, COP_{HT} is the energy efficiency ratio of the electric HP, and P^t_{HP} is the rated power of the electric HP.

The cost formula of electric HP is as follows:

$$C_{HP} = \rho_{HP} P^t_{HP}$$

ρ_{HP} is the cost coefficient of electric HP.

3.2.6 Absorption chiller (ACH)

The upper end of the ACH is connected with a lithium bromide unit, and by absorbing the waste heat released by the gas turbine, the state change reaction of substances is generated to provide cooling energy. The machine is driven by thermal energy, and waste heat can be used to improve energy efficiency. When the heat of H^t is input, the formula of refrigeration power is as follows:

$$CL^t_{ACH} = \mu_{ACH} H^t_{ACH}$$

μ_{ACH} is the energy efficiency ratio of the ACH, and H^t_{ACH} is the input heat of the ACH.

The cost formula of the ACH is as follows:

$$C_{ACH} = \rho_{ACH} P^t_{ACH}$$

ρ_{ACH} is the cost coefficient of the ACH.

3.2.7 Electric refrigerator (ER)

ER generates cooling energy by consuming electric energy. It has been popularized thanks to its convenient installation and high refrigeration efficiency. Its refrigeration formula is as follows:

$$CL^t_{ER} = \mu_{ER} P^t_{ER}$$

μ_{ER} is the energy efficiency ratio parameter of the ER, and P^t_{ER} is the power of the ER.

The cost formula of the ER is as follows:

$$C_{ER} = \rho_{ER} P^t_{er}$$

ρ_{ER} is the cost coefficient of the ER.

3.2.8 Storage of battery (SB)

SB device can store surplus electricity of the integrated energy system, which will be released when the system needs electricity. It can balance the load, reduce the fluctuation and uncertainty of renewable energy, and achieve peak clipping and valley filling in the whole park-level integrated energy system. When the SB device is charged and discharged, the discharging will stop when it reaches 25% of the rated capacity. The charging and discharging formula is as follows:

$$K_{SOC} = \frac{C_s(t)}{C_t}$$

K_{SOC} is the storage state function of the battery, $C_s(t)$ is the residual current, and C_t is the battery capacity.

The cost function of the SB device is as follows:

$$C_{SB} = \rho_{SB}|P_{SB}|$$

ρ_{SB} is the battery cost parameter. P_{SB} is the output of the SB device, standing for power discharge when it is positive and power storage when it is negative.

3.3 Constraints

3.3.1 Objective function

The primary objective of the study is to assist new energy companies in penetrating the market, therefore it is crucial to consider both the environmental impact of the industry and the financial aspects of the enterprise. For this reason, environmental cost is added to the objective function. Businesses must prioritize reducing carbon dioxide emissions while also enhancing the economy:

$$\begin{aligned} min\, F^c = &\sum_{i=1}^{n}\left[\left(C_{PV}^i + C_{WT}^i + C_{FC}^i + C_{MT}^i + C_{HP}^i + C_{ACH}^i + C_{ER}^i + C_{SB}^i\right)\right] \\ &+ C_{OM} + \sum_{t=1}^{24}\left[C_b^t P_b^t - C_s^t P_s^t\right] + \sum_{i=1}^{n}\sum_{o=1}^{m} C_o \mu_{oi} P_{si} + C_{A,m} + C_{s,n} \end{aligned}$$

C_{OM} is the operation and maintenance cost of the integrated energy system, C_b^t and C_s^t indicate the prices of buying and selling electricity per unit time of the integrated energy system, and P_b^t and P_s^t refer to the quantities of electricity bought and sold of the integrated energy system. C_o is the environmental cost coefficient, μ_{oi} is the pollution gas emission coefficient, and P_{si} is the total output power of the integrated energy system.

3.3.2 Power constraints

In order to ensure the life quality of users within the region, power constraints should be imposed inside the integrated energy system.

$$\begin{aligned} &P_{PV}(t) + P_{WT}(t) + P_{FC}(t) + P_{MT}(t) + P_{SB}(t) + P_B(t) \\ &\quad = P_S(t) + P_{HP}(t) + P_{ER}(t) + P_{US}(t) \end{aligned}$$

$P_{US}(t)$ is the electric energy load required by the user side of the park-level integrated energy system.

$$Q_{MT}(t) + Q_{HP}(t) = Q_{US}(t) + Q_{ACH}(t)$$

$Q_{US}(t)$ is the heating energy load required by the user side of the park-level integrated energy system.

$$C_{ACH}(t) + C_{ER}(t) = C_{US}(t)$$

$C_{US}(t)$ is the cooling energy load required by the user side of the park-level integrated energy system.

3.3.3 Operation constraints of energy storage units

The energy storage unit can both generate and store power, so the constraints of energy storage units determine the flexibility of the integrated energy system.

$$P_{SB}^{min}(t) \ll P_{SB}^{i}(t) \ll P_{SB}^{max}(t)$$

$$\sum_{t=1}^{T} P_{SB}^{i}(t)\Delta T = 0$$

$P_{SB}^{min}(t)$ and $P_{SB}^{max}(t)$ refer to the minimum power and maximum power during charging and discharging of the battery.

3.3.4 Network security constraints

The integrated energy system is linked to the energy network at a higher level. In order to ensure the security of the energy network and minimize the potential security hazards, security constraints are required to be imposed on the lines.

$$f_{k,t}^{DM} = \sum_{N} \delta_{K,N}\left(e_{n,g}P_{gt}^{DM} - D_{gt}^{DM}\right)$$

$$F_{K,T}^{min} \ll f_{k,t}^{DM} \ll F_{K,T}^{max}$$

$\delta_{K,N}$ is the line coefficient, and $F_{K,T}{}^{min}$ and $F_{K,T}{}^{max}$ are the upper and lower limits of allowable power of the lines in the system.

4 Example simulation

This study uses an economic development zone in East China as a case study. The newly established economic development zone covers a large number of industrial parks or residential areas under construction, which is appropriate for this study. Therefore, the industrial zone in the park is selected, for example, analysis. The load characteristics of the industrial zone including multiple energy demands (electricity, heating energy, and cooling energy) and relatively stable energy consumption without obvious fluctuations could help to simplify the model operation. The regional load forecast can be illustrated in Figure 5.

4.1 Algorithm introduction

The integrated energy system features complex models and numerous constraints, thus it is hard to figure out the optimal local solution. In this paper, a new heuristic intelligent optimization algorithm, Mayfly Algorithm (Zervoudakis and Tsafarakis, 2020), is adopted. With its precision and speed in the local optimization process, it is well-suited for addressing intricate model optimization challenges.

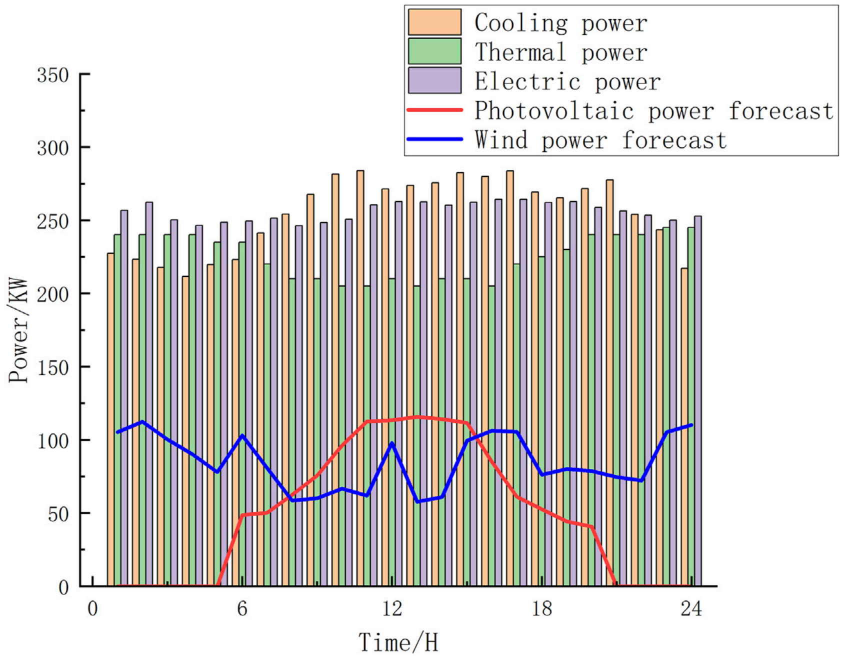

FIGURE 5
Regional load forecast.

The Mayfly Algorithm is based on the simulation of the mating and flight processes of mayflies. As it converges quickly and is of great research significance during local optimization and global search, it is suitable for solving the optimization model of the integrated energy system (Wei et al., 2021).

(a) Activity of male mayflies

Male mayflies usually court the female ones in groups, and the algorithm simulates the position update of each male mayfly by updating individual mayflies in the neighborhood:

$$X_i^{t+1} = X_i^t + V_i^{t+1}$$

X_i^{t+1} and V_i^{t+1} refer to the position and flight velocity of the male mayflies during iteration. The expression of flight velocity is as follows:

$$V_{in}^{t+1} = V_{in}^t + a_1 e^{-\beta r_p^2}\left(pt_{in} - X_{in}^t\right) + a_2 e^{-\beta r_p^2}\left(gt_{in} - X_{in}^t\right)$$

a_1 and a_2 indicate the velocity influence constants of the best individual mayfly during flight, taking 1 and 1.5. pt_{in} is the best position of the mayfly in record and gt_{in} is the best position of an individual mayfly. The best individual in the group will show its courtship posture, with the expression as follows:

$$V_{in}^{t+1} = V_{in}^t + m^* r$$

m is the behavior coefficient, taking 5. r is a random number within the range of $[-1, 1]$.

(b) Activity of female mayflies

According to the individual characteristics of male mayflies, female mayflies fly to males for mating based on the principle of one-to-one mapping. Their position update is similar to that of males, with the flight velocity expression as follows:

$$V_{in}^{t+1} = \begin{cases} V_{in}^t + a_2 e^{-\beta r_p^2}\left(X_{in}^t - Y_{in}^t\right), \\ V_{in}^t + fl^* r, \end{cases}$$

fl is the random walk coefficient.

(b) Mating behavior of mayflies

Assuming that two offspring are generated by crossover after successful mating, then the expression is as follows:

$$f(1) = L^* X_{male} + (1 - L)^* X_{female}$$
$$f(2) = L^* X_{female} + (1 - L)^* X_{male}$$

X_{female} and X_{male} are the locations of the female and male parents.

4.2 Algorithm performance verification

A variety of test functions are used to prove the solving ability of Mayfly Algorithm. The test functions are Generalized Schwefel's Problem, Generalized Penalized Function, and Goldstein-Price Function. The Mayfly Algorithm proposed in this paper is compared with Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Northern Goshawk Optimization (NGO), which are also bionic intelligent optimization algorithms.

The comparison results are shown in the figure:

It can be seen from Figures 6, 7, 8, the advantages of Mayfly Algorithm in optimizing problems can be directly observed from the

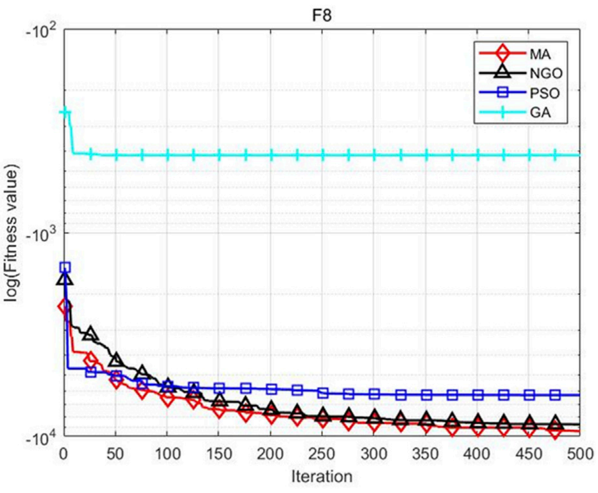

FIGURE 6
The result of Generalized Schwefel's Problem.

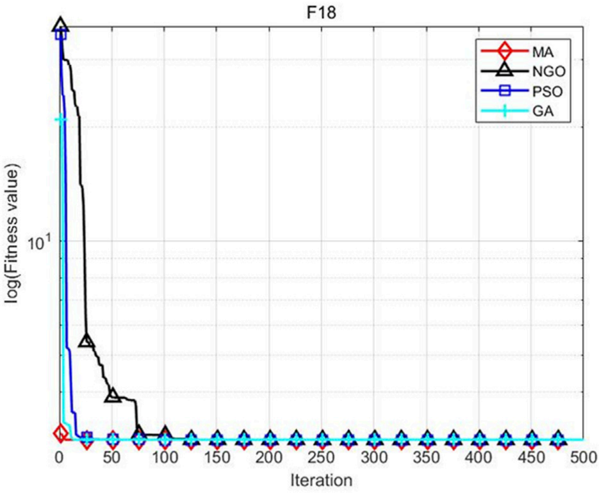

FIGURE 8
The result of Goldstein-Price Function.

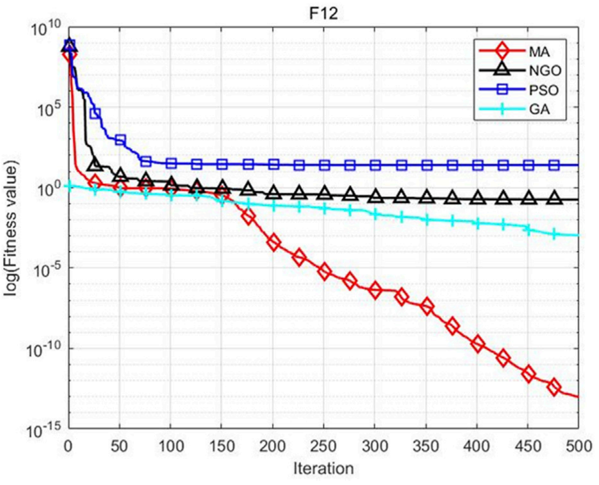

FIGURE 7
The result of Generalized Penalized Function.

figure. Mayfly Algorithm is highly sensitive to the function and its solution state is relatively stable. The test functions show that the Mayfly Algorithm has better convergence speed and stability, the solving result is excellent.

4.3 Example analysis

Scenario 1: In the absence of balancing service, the traditional particle swarm optimization (PSO) is applied optimize the solution based solely on the energy constraints within the system and the initial demand side value.

Scenario 2: Leaving out the balancing service, the intelligent optimization algorithm is adopted for local optimization.

Scenario 3: Taking into account the balancing service, the intelligent optimization algorithm is utilized to break down the energy circulation barrier on a small scale and optimize the scheduling of the model.

In this example, with the initial population size of mayflies set at 100, the analysis on the feasibility of the model is conducted using Matlab2018 platform and the control group.

According to the figures above, it can draw a conclusion that although the simulation results of Scenario 1 can meet the needs of users, the power of gas turbine is excessively high so that a large amount of carbon dioxide will be released. This goes against the primary goal of energy conservation and emissions reduction in the integrated energy system. Meanwhile, Scenario 1 is highly dependent on the major power grid, and needs to purchase high-power electricity to meet the demand of users. The carbon dioxide emissions caused by traditional thermal power generation also seriously damage the environmental performance of the system (Figure 9). Compared with Scenario 1, the gas turbine in Scenario 2 is provided with a lower power, but more electric heat pumps and electric refrigerators are started. Based on the example results, if the new energy generator set operates at lower power levels, the system will buy high-power electricity from the main power grid. Meanwhile, at the peak of energy consumption, the gas turbine's unit power is nearing its maximum capacity, potentially shortening the equipment's lifespan and compromising the system's stability (see Figure 10) Scenario 3 demonstrates a relatively balanced utilization of each unit, without any instances of units approaching the upper power limit at specific time intervals. Meanwhile, the system uses electrical units more frequently, which can ensure the absorption performance of new energy power generation in the system. When the power demand on the user side cannot be met, it is preferred to get power from nearby parks instead of using that from traditional generator sets, thus enhancing environmental performance (Figure 11).

Merely focusing on environmental optimization within the integrated energy system is insufficient for service providers to penetrate the energy market and undertake additional integrated energy system projects for practical implementation. Therefore, the

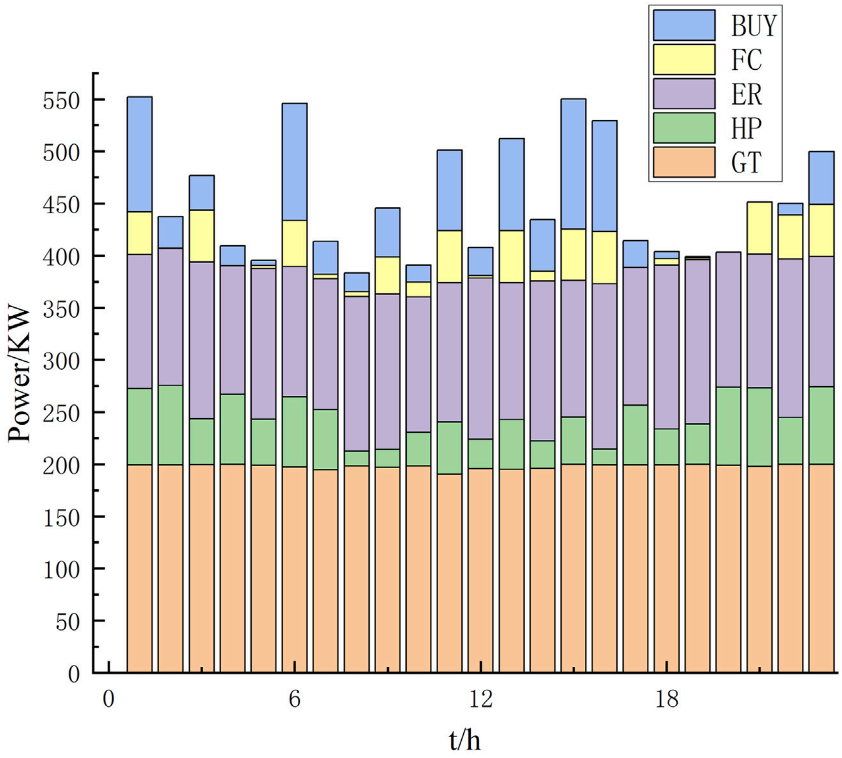

FIGURE 9
Scenario 1.

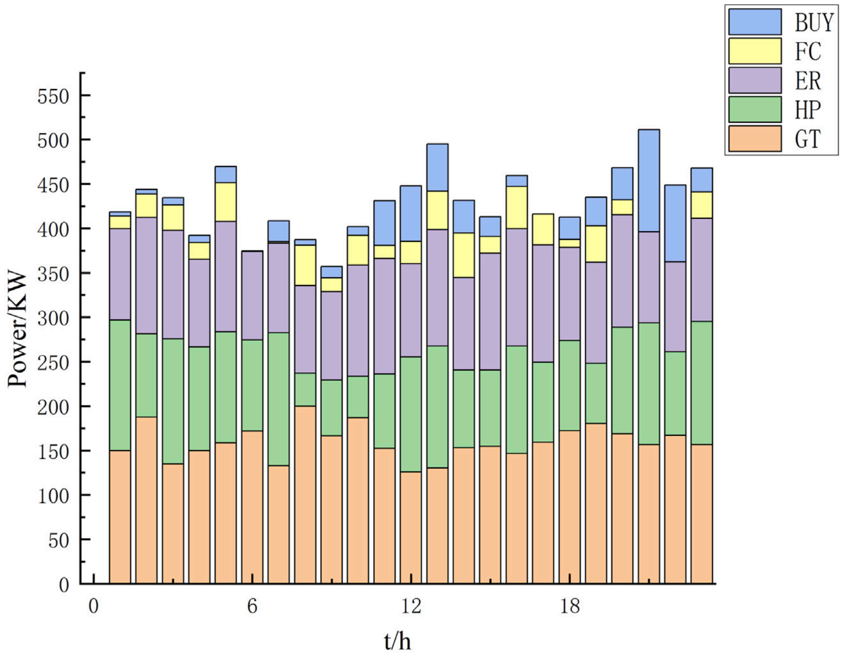

FIGURE 10
Scenario 2.

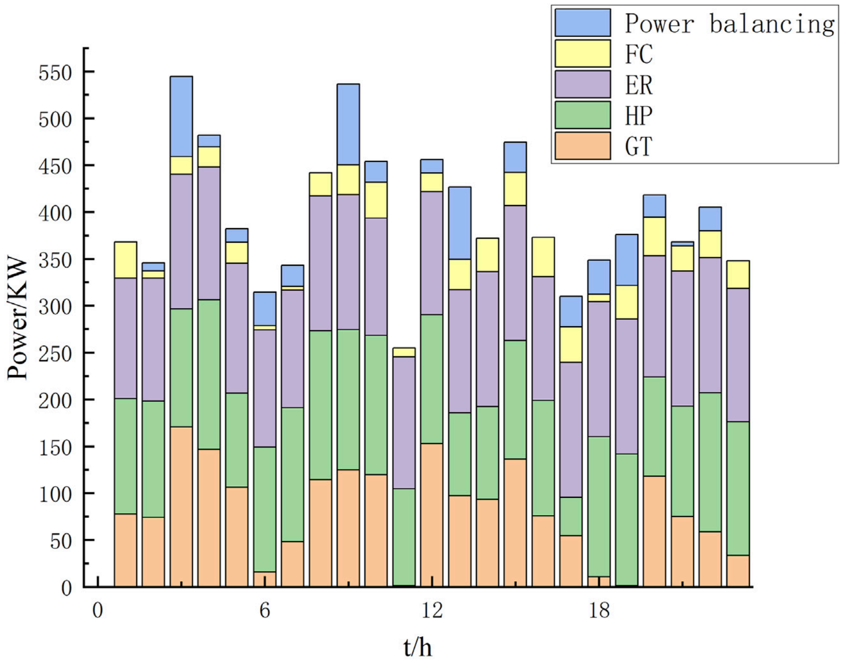

FIGURE 11
Scenario 3.

TABLE 2 Cost accounting table (a).

Cost	Scenario 1	Scenario 2	Scenario 3
Electricity	4,430.69 yuan	2,438.41 yuan	1,943.27 yuan
Natural gas	1,416.51 yuan	1,153.87 yuan	689.32 yuan

TABLE 3 Cost accounting table (b).

Cost	Scenario 1	Scenario 2	Scenario 3
Electricity	4,430.69 yuan	2,438.41 yuan	2,043.27 yuan
Natural gas	1,416.51 yuan	1,153.87 yuan	1,189.83 yuan
Additional costs	—	—	620 yuan

economy of the balancing service mode should also be analyzed. Scenario 3 will increase the balancing service cost (adjustment cost, etc.), which is compared by 30 days.

As can be seen from Table 2, the cost of Scenario 3 is the lowest, with improved economy. However, if taking into account the increased penalty expenses caused by the service provider failing to perform the contract due to irresistible factors, as well as the additional costs such as the repair and maintenance expenses of each unit of the integrated energy system, the costs will be higher than those of Scenario 2 and roughly the same as those of Scenario 1 (Table 3). Therefore, in the research afterwards, how to ensure the stability of the integrated energy system will remain the focus.

In terms of environmental benefits, this can be seen from Table 4, scenario 3 has lower carbon emissions, emitting 3869.9000 kg of carbon dioxide in daily scheduling operation, while scenario 1 and Scenario 2 have carbon dioxide emissions of 4633.2738 kg and 4536.2645 kg, respectively. It is obvious that scenario 3 is more environmentally friendly.

TABLE 4 Carbon dioxide emissions.

	Scenario 1 (kg)	Scenario 2 (kg)	Scenario 3 (kg)
carbon dioxide emissions	4633.2738	4536.2645	3869.9000

5 Conclusion

In the past few years, the technology application and demonstration projects of the integrated energy industry in China has achieved phased results. Meanwhile, China's immature electricity market reform, limited policy objectives, coordination mechanism and reward and punishment mechanism have become key factors hindering the development of integrated energy industry. Therefore, based on the principle of minimizing the reform cost, this paper puts forward the balancing service optimization scheme of the park-level integrated energy system. From the standpoint of IES providers, the scheme can realize highly efficient absorption of new energy in the park-level integrated energy system through energy interaction among parks within the region given that the benefits of service providers are guaranteed. Compared with the current integrated energy market subject to the traditional power market regulation mechanism, this balancing service mode enables the source energy of service providers to be independent from the traditional power grid, thus avoiding investment risks brought by disruptive market reform cost and high-dimensional information cost.

Through the case analysis, the results show that the optimal daily operating cost is 2632.59 yuan and the daily carbon emission is 3869.90 kg under the typical industrial scenario. The daily operation cost and daily carbon dioxide emission are significantly lower than that of the integrated energy system under the ordinary optimization mode. According to the case analysis and research, the following conclusions can be drawn. The integrated energy balancing service mode can reduce the traditional thermal power generation, increase the absorption of new energy generation, and thus improve the environmental performance within the park. With this mode, service providers are able to cut down investment costs, promote market equilibrium and optimization with minimal information interaction, and significantly lower transaction costs caused by information asymmetry. In addition, the study suggests that there should be more scheduling centers on the same level as service providers and energy networks, instead of relying on scheduling of the traditional thermal power grid; the information dimension should be lowered while ensuring the energy demand of the user side; the IES provider should take into consideration the added value brought by the integrated energy under the Dual Carbon goals in addition to the energy price cost. The integrated energy balancing services can effectively cope with the difficult situation facing the Chinese integrated energy enterprises about how to enter the integrated energy service market. The conclusions and suggestions of the study can provide valuable reference for the immature integrated energy service industry of many developing countries.

In our upcoming research, we will focus on the following areas. (1) Include carbon emission rights trading and green certificates trading into the integrated energy industry. Conduct further analysis on the advantages of the integrated energy system in energy saving and emission reduction to stimulate the potentials of the new energy market. (2) Further explore the enterprise factors, enterprise attributes, innovation environment and market demand behind the integrated energy services. (3) In order to optimize the synergy effects among different players and the allocation efficiency of resources from service providers, further explore the cooperative communication and integrated development policies between IES providers and higher-level energy networks. (4) Further improve the stability of the integrated energy system. Further reduce additional costs incurred by service providers due to force majeure or equipment failure factors.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HP: Conceptualization, Data curation, Investigation, Methodology, Software, Supervision, Writing–original draft. YL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Resources, Writing–original draft. RL: Formal Analysis, Funding acquisition, Writing–original draft. HZ: Formal Analysis, Project administration, Validation, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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