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Research Article

Research on Optimization and Scheduling of Multi-Integrated Energy System Based on Step-by-Step Carbon Trading and Hybrid Games

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In light of the current integrated energy system (IES) transactions, the interaction between the supply and demand sides is not fully considered. With the overall development of the carbon trading market, there is a need to deeply explore the interests of multiple entities in energy trading under the step-by-step carbon trading mechanism. Therefore, research on the optimization and scheduling of multicomprehensive energy systems based on step-by-step carbon trading and hybrid games is proposed. Firstly, the interests and demands of various integrated energy systems and users in multi-integrated energy system energy trading should be comprehensively considered. Based on the master-slave game and Nash bargaining theory, an optimization model of multiple integrated energy systems is built under the step-by-step carbon trading mechanism and load aggregation, representing the interests of the entire user side. Secondly, the proposed game optimization model has been established to prove it can maximize social benefits. IES and user game optimization models have been established, with multi-IES being leaders with the goal of maximizing their own benefits, guiding the optimization between IES and load by formulating energy prices. Users are followers who aim to maximize comprehensive benefits and respond to IES's decisions through cooperation. Finally, using the improved gray wolf algorithm to solve the built model, it has been proven through comparison of calculation examples that the proposed method can reduce carbon emissions, effectively coordinate the optimization scheduling of multi-IES, and achieve the fair distribution of multi-IES cooperation benefits. This improves the effectiveness of individual and social benefits.

1. Introduction

To achieve China's "dual carbon" target, the energy industry, as one of the main sources of carbon emissions, needs to reduce the level of carbon emissions in the process of energy production and conversion, gradually reduce the use of fossil fuels, and vigorously develop clean energy, accelerating the substitution of clean energy for traditional fossil fuels [1–3]. Under the background of China's "dual carbon" target, clean energy such as wind power and photovoltaics will gradually become the main energy form in China's energy structure. The comprehensive energy system can effectively help absorb renewable energy through various generalized storage effects and is an effective solution to achieve the dual carbon target. With the development of multiple IES, there are often multiple IES in the same distribution network area, forming an IES alliance. The IES can make full use of the idle resources of each IES through various energy transactions between alliances and improve the response capability to demand of the IES alliance [4, 5]. In addition, the comprehensive energy system has the strengths of energy cascade application and multienergy combination complementarity, which can significantly improve the exploitation rate of clean energy, and will be one of the essential solutions for the achievement of low-carbon development in the energy industry. The coordinated operation of various coupling devices can reduce greenhouse gas emissions, and the complementary substitution characteristics of load-side dispatchable resources can also reduce greenhouse gas emissions. Therefore, considering the interaction of interests and supply-demand interaction between multiple comprehensive energy systems, it is necessary to seek a fair and reasonable operation and control method.

Currently, scholars at home and abroad have carried out a lot of research on IES. Literature [6] establishes an IES composed of a CCHP system, which adopts a centralized bus-based approach to improve the flexibility and adaptability of equipment capacity configuration and improve the stability of system operation. Literature [7] establishes a CCHP multi-IES optimization scheduling study based on electrical energy interaction, aiming for minimal cost, using the alternate direction multiplier method (ADMM) for distributed solution. Literature [8] establishes a cold-thermal multi-IES model containing energy storage, aiming for the minimum operating cost of the multi-CCHP micronetwork service of energy storage power stations and solves the model through the 0-1 hybrid integer linear method, which realizes the elimination of multi-microgrid new energy power generation and reduces the operating cost of the system. However, the above literature ignores the interest interaction between users and IES, so it is necessary to find a reasonable way to optimize scheduling to consider the interest relationship between multiple IES and the interaction between user-side and multiple IES. Currently, scholars at home and abroad have carried out a lot of research on IES optimization scheduling and energy trading. Literature [9] proposes that the CCHP multi-IES containing electrical energy interaction is optimized with the goal of minimum overall cost, but does not take into account the information privacy of each participating entity. Literature [10] aims for the lowest loss and uses the alternating direction multiplier method for distributed solution. In literature [11], two-way comprehensive demand response models are set up between comprehensive power generation sites, load aggregators, and consumers. At the same time, a hybrid integer quadratic programming—multi-inverse optimization—distributed algorithm is proposed to solve the game model. The utility of all parties can be maximized and the balance of interests can be achieved in the continuous interactive game process. Literature [12–14] focuses on the interaction between multiple IES and the upper network as a whole, establishing an optimized scheduling model for the interest interaction between the upper network and IES.

According to research on demand response in integrated energy systems (IES), it can be divided into single demand response and integrated demand response (IDR) based on the form of response energy. According to the form of response measures, it can be divided into price DR, incentive DR, and alternative DR [15]. The above DR forms can improve the user load curve, cut the peak, and fill the valley. Relevant scholars have also studied these DR forms in IES. Literature [16] considers new energy and load fluctuations and establishes a three-layer rolling-based optimization scheduling model using the characteristics of price-based DR and alternative DR. Literature [17] establishes a recent economic scheduling model considering incentive-oriented comprehensive demand response with the goal of minimum operating cost. Literature [18] proposes a multicriteria optimization scheduling model for a coordinated energy system, taking into account the behavior of the demand for combined electro-thermal energy. Literature [19] proposes a grid planning model based on a two-layer dynamic game by constructing a single stakeholder planning profit model, adopting a robust optimisation algorithm to deal with the uncertainty of wind power output, and introducing a virtual player, "Nature", to represent the uncertainty in the game process. Literature [20] establishes a double-layer optimization scheduling model of the double-main ladder carbon trading mechanism involving users and IES operators, based on the current background of "double carbon," where the load of user-side participation in demand response is divided into rigid load, price-sensitive load, and carbon price-sensitive load. To sum up, the research on IDR in IES is in its infancy, and there is a lack of interaction between the demand side and the energy supply side. The transmission in the information flow cannot be accurately controlled. In addition, IDR takes less consideration of the distribution characteristics of various energy sources in time and space, and the advantages of the user-side have not been fully utilized. Therefore, the combination of IDR and IES and the use of refined modeling are of great significance for demand response to participate in the IES.

When it comes to optimizing the scheduling of multiple IES subjects, the optimization theory of a single IES planning is no longer applicable due to the competition of interests between IES subjects. Therefore, the strategic equilibrium analysis method based on engineering game theory has emerged [21]. Considering the competition and cooperation of each subject in the game, game theory is divided into noncooperative games and cooperative games. As a result, scholars both domestically and abroad have studied the application of game theory in multienergy coupled energy systems. In literature [22], an independent scheduling model is proposed for decentralised market agents at the load level, together with a P2P trading system that takes into account the existence of a noncooperative multiagent game. The power, gas, and heat exchanges in the regional electricity market are being modeled, and a common settlement mechanism for the energy coupling market is being defined. In literature [23], an energy storage sharing framework is proposed that considers both storage capacity and power capacity. A noncooperative game is formed between the relationship between producers and consumers because each producer and consumer want to minimize the cost of behavior. In literature [24], an optimal day scheduling model for multiple IES is proposed that considers comprehensive demand response, cooperative games, and virtual energy storage in order to maximize the overall interests of the cooperation alliance. The cooperative game theory is used to consider the energy trading scheme between multiple IES, and the Nash negotiating method is used to solve the problem of the cooperative game and obtain a balanced and Pareto efficient energy sharing strategy. Literature [25] proposes a two-stage energy management approach for thermoelectric integrated energy systems considering dynamic pricing and operation strategy optimization of the Stackelberg game, which establishes a two-stage energy management framework for the interactions between energy service providers and users by considering the general integrated energy efficiency of electrical and thermal exergy characteristics, but it does not take into account the optimization of the game for multi-IES.

Furthermore, with the proposal of the dual-carbon goal, China's carbon trading market is in an all-round development stage [26]. Under the carbon trading mechanism, more literature research has been conducted on the low-carbon operation of the comprehensive energy system with only a single interest subject [27, 28]. However, there are few literatures analyzing the positive effects of multistakeholder interaction under the carbon trading mechanism and multisubject cooperative operation on the reduction of carbon emissions.

In summary, this paper considers the interest interaction between multi-IES and the supply-demand interaction between IES operators and users under the step-by-step carbon trading mechanism. It proposes a multi-IES optimization scheduling based on step-by-step carbon trading and hybrid game. This method combines the step-by-step carbon trading mechanism, comprehensively considers the interests of various IES and users in multiple IES, and builds a load aggregator optimization model of multi-IES operators and user-side interests based on hybrid game theory. In this paper, the improved gray wolf algorithm is used to solve the problem, which proves the effectiveness of the proposed method through examples, ensures the interests of each subject, and analyzes the comprehensive reasons for optimizing operation and reducing carbon emissions under the step-by-step carbon trading mechanism.

2. Multi-IES Framework with Step-by-Step Carbon Trading Mechanism

2.1. The Framework of Multi-IES. The multi-integrated energy system studied in this paper is illustrated in Figure 1. Multiple integrated energy systems form the IES alliance and realize energy interaction through power pipelines, heat pipelines, cooling pipelines, and natural gas pipelines. The price of energy purchased by each IES from other IES is uniform. The main equipment included in the integrated energy system is photovoltaic (PV), electric energy storage (EES), microgas turbine (MT), heat recovery steam generator (HRSG), thermal energy storage (TES), absorption chiller (AC), electric refrigerator (ER), and cold energy storage (CES). The energy conversion relationship of a single integrated energy system is shown in Figure 2. Each integrated energy system interacts with the upper power grid and can purchase the necessary natural gas for the operation of the energy conversion equipment from the superior natural gas network to supply electrical energy, thermal energy, cold energy, and gas energy to the internal load of IES. Any excess energy can be stored.

2.2. Stepped Carbon Trading Mechanism Model. Stepped carbon trading is a carbon market system in which carbon allowances or prices are set at progressively lower levels to encourage IESs to gradually reduce their GHG emissions. The goal of this mechanism is to gradually reduce overall carbon emissions over time, thereby creating the conditions for combating climate change. In stepped carbon trading, the control of carbon emissions is gradually tightened, thus providing time for social and economic systems to adapt and transform. Its core idea is to incentivise various stakeholders to take measures to reduce emissions by progressively lowering carbon emission allowances or prices, prompting the IES to adopt cleaner production methods, energy sources, and technologies in order to reduce adverse impacts on the climate.

2.2.1. Quota Models of Carbon Emission. Carbon emission allowances are a policy tool used to control greenhouse gas emissions and are designed to limit carbon emissions from IES. The model is based on allocating a certain number of carbon emission allowances to participants, who need to ensure that their actual emissions do not exceed the allocated allowances. If a participant's actual emissions exceed their quota, they may need to purchase additional allowances or face punitive measures such as fines. In this paper, the main types of system-caused carbon emissions are the following coal-fired power plants in the upper grid and GT and GB units within the IES system. In this paper, the carbon emission allowances are as follows:

$$\begin{cases} E_q^{\mathrm{IES}} = E_q^{\mathrm{GRID}} + E_q^{\mathrm{GT}} + E_q^{\mathrm{GB}}, \\ E_q^{\mathrm{GRID}} = \mu_e \sum_{t=1}^{T} P_t^{\mathrm{GRID}}, \\ E_q^{\mathrm{GT}} = \mu_g \sum_{t=1}^{T} P_t^{\mathrm{GT}}, \\ E_q^{\mathrm{GB}} = \mu_g \sum_{t=1}^{T} P_t^{\mathrm{GB},h}, \end{cases} \tag{1}$$

where E_q^{GRID}, E_q^{GT}, and E_q^{GB} are the emission quotas of the electricity purchase, GT and GB, respectively; μ_e and μ_g are the baseline carbon credits per each unit of electric power generated and gas used for coal and gas-fired units, respectively; P_t^{GRID} is the purchased power at time t; P_t^{GT} is the total output of GT at time t; $P_t^{\mathrm{GB},h}$ is the output of GB at time t; and T is the running cycle.

2.2.2. Practical Models of Carbon Emission. Since CO_2 can be absorbed by carbon capture systems, it can be included in the considered carbon emissions as

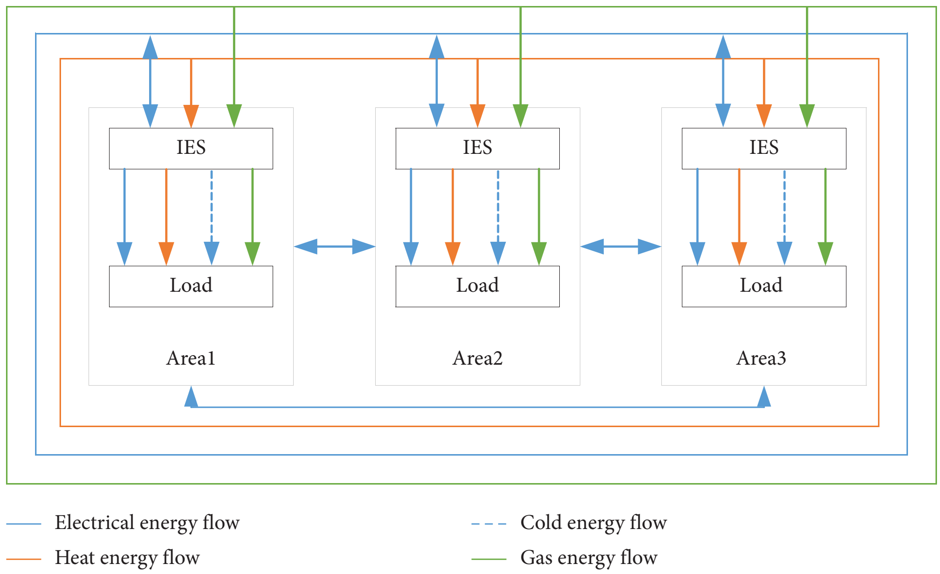

FIGURE 1: Multi-IES system diagram.

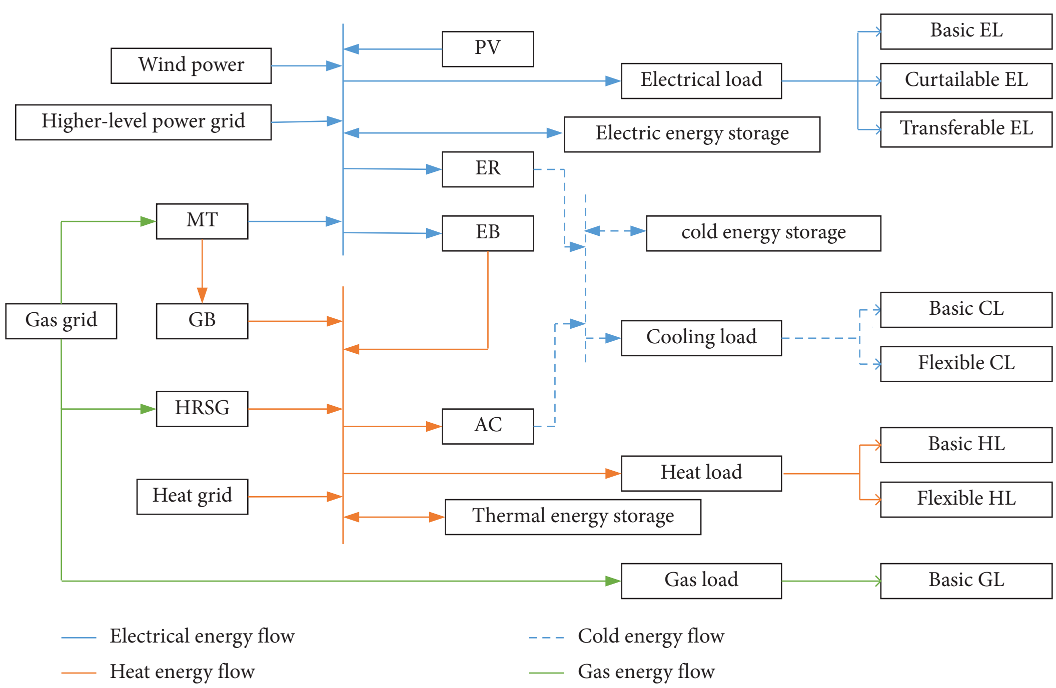

FIGURE 2: Single IES energy conversion relationship diagram.

$$\begin{cases} E_a^{\mathrm{IES}} = E_a^{\mathrm{GRID}} + E_a^{\mathrm{GT}} + E_a^{\mathrm{GB}} - E_a^{\mathrm{CO_2}}, \\ E_q^{\mathrm{GRID}} = \delta_e \sum_{t=1}^{T} P_t^{\mathrm{GRID}}, \\ E_q^{\mathrm{GT}} = \delta_g \sum_{t=1}^{T} P_t^{\mathrm{GT}}, \\ E_q^{\mathrm{GB}} = \delta_g \sum_{t=1}^{T} P_t^{\mathrm{GB},h}, \end{cases} \tag{2}$$

where E_a^{GRID}, E_a^{GT}, and E_a^{GB} are the actual carbon dioxide emissions from electricity purchases, GT and GB, respectively; $E_a^{\mathrm{CO_2}}$ is the total amount of CO_2 that captured; and δ_e and δ_g are the carbon dioxides emitted by the coal and gas power plants, respectively.

2.2.3. Ladder-Type Carbon Trading Model. After the above process and the analysis of the model, it can be found out that the amount of carbon emission rights trading involved in the carbon trading market is

$$E_r^{\mathrm{IES}} = E_a^{\mathrm{IES}} + E_q^{\mathrm{IES}}. \quad (3)$$

Compared with the traditional carbon trading pricing mechanism, in order to further limit carbon emissions, this paper adopts the ladder pricing mechanism. Its basic principle is to divide the whole emission reduction process into multiple steps according to the emission reduction target. Each ladder represents a specific time period, and within each ladder, the regulator will set a specific carbon emission quota or price. Because the cost of laddered carbon trading is

$$C_{\mathrm{CO_2}} = \begin{cases} B_{\mathrm{CO_2}} E_r^{\mathrm{IES}}, & E_r^{\mathrm{IES}} \le l, \\ B_{\mathrm{CO_2}}\left[E_r^{\mathrm{IES}}\left(1+\gamma_{\mathrm{CO_2}}\right) - l\gamma_{\mathrm{CO_2}}\right], & l \le E_r^{\mathrm{IES}} \le 2l, \\ B_{\mathrm{CO_2}}\left[E_r^{\mathrm{IES}}\left(1+2\gamma_{\mathrm{CO_2}}\right) - 3l\gamma_{\mathrm{CO_2}}\right], & 2l \le E_r^{\mathrm{IES}} \le 3l, \\ B_{\mathrm{CO_2}}\left[E_r^{\mathrm{IES}}\left(1+3\gamma_{\mathrm{CO_2}}\right) - 6l\gamma_{\mathrm{CO_2}}\right], & 3l \le E_r^{\mathrm{IES}} \le 4l, \\ B_{\mathrm{CO_2}}\left[E_r^{\mathrm{IES}}\left(1+\gamma_{\mathrm{CO_2}}\right) - 10l\gamma_{\mathrm{CO_2}}\right], & E_r^{\mathrm{IES}} \le 4l, \end{cases} \quad (4)$$

where $B_{\mathrm{CO_2}}$ is the system's benchmark carbon trading price; $\gamma_{\mathrm{CO_2}}$ is the increase in the tax price; and l is the length.

3. Multi-IES Two-Stage Optimized Scheduling Model considering Step-by-Step Carbon Trading Mechanism and Comprehensive Demand Response

The basic framework of the hybrid game is shown in Figure 3. This paper builds the IES and load aggregation business master-slave game model of the embedded load aggregator cooperative game to take into account the respective interests of IES and load aggregator members. The process of implementation can be broken down into two main stages.

3.1. Stage 1: Master-Slave Game between IES and Load Aggregator.

IES will adjust the energy price based on the purchase and sale of energy demand provided by the load aggregator to maximize its own benefits and then send the energy price to stage two. The load aggregator will integrate user load data through the user energy management system and initially formulate the plan for the negative energy that each IES needs to bear. By determining the amount of energy required by each participant, the energy transaction price between each participant is determined to obtain the final income of each party. Each participant only needs to communicate their expected energy transaction price to other participants to obtain an energy transaction price acceptable to all parties, ensuring their respective interests and needs are met and ensuring the willingness of all parties to participate in energy cooperation.

3.1.1. Multi-IES Objective Function.

The goal of multi-IES is to optimize its own revenue, taking into account its own expenses and energy sales earnings, because the performance claim of multi-IES can be expressed as

$$\max U_i = I_{i,\mathrm{sell}} + I_{i,\mathrm{trade}} - C_{i,\mathrm{eq}} - C_{i,\mathrm{grid}} - C_{i,\mathrm{trade}} + C_{\mathrm{co_2}}, \quad (5)$$

where $I_{i,\mathrm{sell}}$ is the revenue from energy sales by integrated energy system operator i to its own customers; $I_{i,\mathrm{trade}}$ is the revenue from energy interactions with other operators; $C_{i,\mathrm{eq}}$ is the energy production cost of gas turbines and gas boilers; $C_{i,\mathrm{grid}}$ is the cost of interactions with the parent network; $C_{i,\mathrm{trade}}$ is the overgrid fee from energy interactions with other integrated energy system operators; and $C_{\mathrm{co_2}}$ is the cost of carbon trading. Specifically,

$$\begin{cases} I_{i,\mathrm{sell}} = \sum_{t=1}^{T}\left(p_{\mathrm{el}}^t P_{i,\mathrm{el}}^t + p_{\mathrm{hl}}^t Q_{i,\mathrm{hl}}^t + p_{\mathrm{cl}}^t L_{i,\mathrm{cl}}^t\right), \\ I_{i,\mathrm{trade}} = \sum_{t=1}^{T}\sum_{j=1,i\ne j}^{D}\left(p_{\mathrm{ij},e}^t P_{\mathrm{ij},e}^t + p_{\mathrm{ij},h}^t Q_{\mathrm{ij},h}^t + p_{\mathrm{ij},c}^t L_{\mathrm{ij},c}^t\right), \\ C_{i,\mathrm{eq}} = \sum_{t=1}^{T}\Big[\omega_1^{\mathrm{GT}}\left(P_{\mathrm{GT},i,t}\right)^2 + \omega_2^{\mathrm{GT}}\left(P_{\mathrm{GT},i,t}\right) + \omega_3^{\mathrm{GT}} + \omega_1^{\mathrm{GB}}\left(H_{\mathrm{GT},i,t}\right)^2 \\ \quad + \omega_2^{\mathrm{GB}}\left(H_{\mathrm{GT},i,t}\right) + \omega_3^{\mathrm{GB}}\Big], \\ C_{i,\mathrm{grid}} = \sum_{t=1}^{T}\left(p_{e,s}^t P_{i,e,b}^t + p_{g,s}^t G_{i,g,b}^t\right) - \sum_{t=1}^{T}\left(p_{e,b}^t P_{i,e,s}^t + p_{g,b}^t G_{i,g,s}^t\right), \\ C_{i,\mathrm{trade}} = \frac{1}{2}\sum_{t=1}^{T}\sum_{j=1,i\ne j}^{D}\Big[\gamma_1^e\left(P_{\mathrm{ij},e}^t\right)^2 + \gamma_2^e\,|P_{\mathrm{ij},e}^t| + \gamma_1^h\left(Q_{\mathrm{ij},h}^t\right)^2 \\ \quad + \gamma_2^h\,|Q_{\mathrm{ij},h}^t| + \gamma_1^c\left(L_{\mathrm{ij},c}^t\right)^2 + \gamma_2^c\,|L_{\mathrm{ij},c}^t|\Big], \end{cases} \quad (6)$$

where $P_{i,\mathrm{el}}^t$, $Q_{i,\mathrm{hl}}^t$, and $L_{i,\mathrm{cl}}^t$ are the electric, thermal, and cooling loads supplied by IES operator i at time t; p_{el}^t, p_{hl}^t, and p_{cl}^t are the electric, thermal, and cooling prices of the multi-IES system at time t, which are set by the IES operator in consultation with the load aggregator. In order to prevent the disruption of market equilibrium in the multi-IES system due to the high or low energy sales price of a single IES at a certain moment, the energy sales price to users in the multi-IES system is a uniform price; $P_{\mathrm{ij},e}^t$, $Q_{\mathrm{ij},h}^t$, and $L_{\mathrm{ij},c}^t$ are the electric power, thermal power, and cold power supplied by IES operator i to IES operator j at time t, with positive values indicating sales and negative values indicating purchases; D is the total number of IESs, which is taken as 3 in this study; $p_{\mathrm{ij},e}^t$, $p_{\mathrm{ij},h}^t$, and $p_{\mathrm{ij},c}^t$ are the electricity, thermal power, and cold power prices traded between IES operator i and IES operator j at time t; $P_{i,e,s}^t$ and $G_{i,g,s}^t$ are the electricity and gas power sold by IES operator i to the superior network at time t, respectively; $p_{e,s}^t$ and $p_{g,s}^t$ are the electricity and gas prices of the superior network at time t, respectively; $p_{e,b}^t$ and $p_{g,b}^t$ are the electricity and gas prices bought back by the

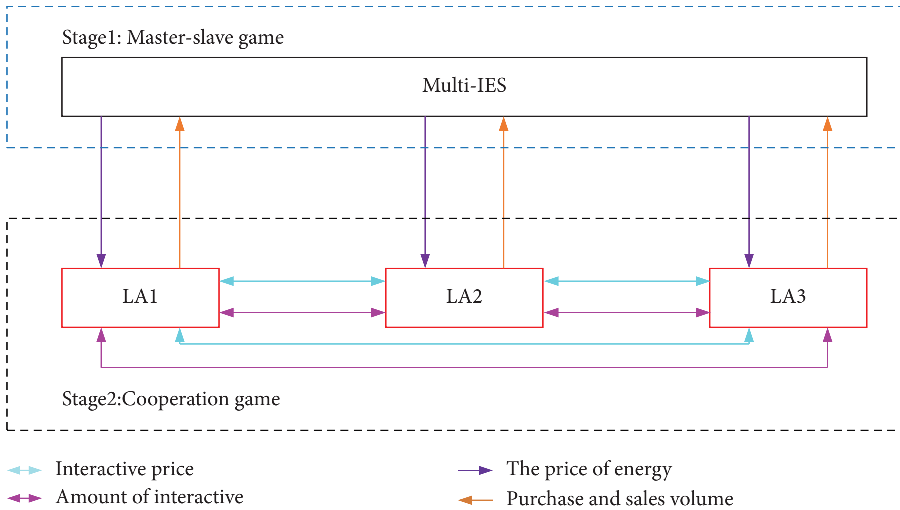

FIGURE 3: Basic framework diagram of the hybrid game.

superior network at time t, respectively; ω_1^{GT}, ω_2^{GT}, ω_3^{GT}, ω_1^{GB}, ω_2^{GB}, and ω_3^{GB} are the cost coefficients of gas turbines and gas boilers, respectively; γ_1^e, γ_2^e, γ_1^h, γ_2^h, γ_1^c, and γ_2^c are the discounting coefficients of overgrid charges.

3.1.2. Constraints. The optimization of the operation of the district integrated energy system needs to follow certain constraints to make the system operate within a safe and reliable range. The energy production of all energy-coupled devices in the district energy system at time h has upper and lower limits:

$$\begin{cases} e_{i,\min,X} \le e_{i,h,X} \le e_{i,\max,X}, \\ g_{i,\min,X} \le g_{i,h,X} \le g_{i,\max,X}, \\ h_{i,\min,X} \le h_{i,h,X} \le h_{i,\max,X}, \\ c_{i,\min,X} \le c_{i,h,X} \le c_{i,\max,X}, \end{cases} \tag{7}$$

where $e_{i,h,X}$, $g_{i,h,X}$, $h_{i,h,X}$, and $c_{i,h,X}$ are the power generation, gas production, heat production, and cooling production of energy-coupled device X of system I, respectively; $e_{i,\max,X}$, $e_{i,\min,X}$, $g_{i,\max,X}$, $g_{i,\min,X}$, $h_{i,\max,X}$, $h_{i,\min,X}$, $c_{i,\max,X}$, and $c_{i,\min,X}$ are the upper and lower limits of power output of energy-coupled device X for electricity, gas, heat, and cooling, respectively.

The system must satisfy the electrical, thermal, and cooling power conservation constraints within the integrated energy system:

$$\begin{cases} P_{\mathrm{mt},i,t} + P_{\mathrm{bs},i,t}^{\mathrm{dis}} + P_{\mathrm{wt},i,t} + P_{\mathrm{pv},i,t} + P_{\mathrm{bug},i,t} = P_{\mathrm{load},i,t} \\ + P_{\mathrm{bs},i,t}^{\mathrm{ch}} + P_{\mathrm{eb},i,t}^{\mathrm{in}} + P_{\mathrm{ec},i,t}^{\mathrm{in}} \\ H_{\mathrm{gb},i,t} + H_{\mathrm{rb},i,t}^{\mathrm{out}} + H_{\mathrm{hs},i,t}^{\mathrm{dis}} = H_{\mathrm{load},i,t} + H_{\mathrm{hs},i,t}^{\mathrm{ch}} + H_{\mathrm{ac},i,t}^{\mathrm{in}} \\ C_{\mathrm{ac},i,t}^{\mathrm{out}} + C_{\mathrm{cs},i,t}^{\mathrm{dis}} + C_{\mathrm{ec},i,t}^{\mathrm{out}} = C_{\mathrm{load},i,t} + C_{\mathrm{cs},i,t}^{\mathrm{ch}}, \end{cases} \tag{8}$$

where $P_{\mathrm{wt},i,t}$ and $P_{\mathrm{pv},i,t}$ are the output power of the wind turbine and photovoltaic units in IES, respectively; $P_{\mathrm{bug},i,t}$ is the purchased power of IES to the distribution network; $P_{\mathrm{mt},i,t}$ is the output power of IES gas turbine; $P_{\mathrm{bs},i,t}^{\mathrm{ch}}$ and $P_{\mathrm{bs},i,t}^{\mathrm{dis}}$ are the charge and discharge power of electric energy storage, respectively; $P_{\mathrm{eb},i,t}^{\mathrm{in}}$ and $P_{\mathrm{ec},i,t}^{\mathrm{in}}$ are the input power of IES electric boiler and electric chiller, respectively; $P_{\mathrm{load},i,t}$ is the electric load of IES; $H_{\mathrm{gb},i,t}$ is the output heat power of IES gas boiler; $H_{\mathrm{hs},i,t}^{\mathrm{ch}}$ and $H_{\mathrm{hs},i,t}^{\mathrm{dis}}$ are the charge and discharge power of thermal energy storage, respectively; $H_{\mathrm{rb},i,t}^{\mathrm{out}}$ is the output heat power of IES waste heat boiler; $H_{\mathrm{ac},i,t}^{\mathrm{in}}$ is the input heat power of IES absorption chiller; $H_{\mathrm{load},i,t}$ is the heat load of IES; $C_{\mathrm{cs},i,t}^{\mathrm{ch}}$ and $C_{\mathrm{cs},i,t}^{\mathrm{dis}}$ are the cold storage charging and discharging power, respectively; $C_{\mathrm{ac},i,t}^{\mathrm{out}}$ is the cold power output of IES absorption chiller; $C_{\mathrm{ec},i,t}^{\mathrm{out}}$ is the cold power output of IES electric chiller; and $C_{\mathrm{load},i,t}$ is the cold load of IES.

To ensure efficient operation, IESi shall not simultaneously purchase and counter-sell electricity to the grid, purchase and deliver electricity to IES, or purchase and deliver heat to the interconnection heat network, purchase and deliver gas to the interconnection gas network, or purchase and deliver cold to the interconnection heat and cold network during time period h:

$$\begin{cases} e_{i,h}^{\mathrm{grid}-b} - e_{i,h}^{\mathrm{grid}-s} = 0, \\ e_{i,h}^{\mathrm{inter}-b} - e_{i,h}^{\mathrm{inter}-s} = 0, \\ g_{i,h}^{\mathrm{inter}-b} - g_{i,h}^{\mathrm{inter}-s} = 0, \\ h_{i,h}^{\mathrm{inter}-b} - h_{i,h}^{\mathrm{inter}-s} = 0, \\ c_{i,h}^{\mathrm{inter}-b} \cdot c_{i,h}^{\mathrm{inter}-s} = 0, \end{cases} \tag{9}$$

where $e_{i,h}^{\mathrm{inter}-b}$ and $e_{i,h}^{\mathrm{inter}-s}$ are the electricity purchased and supplied by IESi from other IESs in time period h; $g_{i,h}^{\mathrm{inter}-b}$ and $g_{i,h}^{\mathrm{inter}-s}$ are the gas energy purchased and supplied and consumed by IESi from other IESs in time period h; $h_{i,h}^{\mathrm{inter}-b}$ and $h_{i,h}^{\mathrm{inter}-s}$ are the heat energy purchased and supplied and consumed by IESi from other IESs in time period h; and

$c_{i,h}^{\text{inter}-b}$ and $c_{i,h}^{\text{inter}-s}$ are the cold energy purchased and supplied and consumed by IESi from other IESs in time period h, respectively.

The interconnection of electrical energy between IESs is also subject to electrical conservation constraints, thermal constraints, gas constraints, and cold constraints:

$$\begin{cases} \sum_{i=1}^{N} e_{i,h}^{\text{inter}-s} - \sum_{i=1}^{N} e_{i,h}^{\text{inter}-b} = 0, \\ \sum_{i=1}^{N} g_{i,h}^{\text{inter}-s} - \sum_{i=1}^{N} g_{i,h}^{\text{inter}-b} \geq 0, \\ \sum_{i=1}^{N} h_{i,h}^{\text{inter}-s} - \sum_{i=1}^{N} h_{i,h}^{\text{inter}-b} \geq 0, \\ \sum_{i=1}^{N} c_{i,h}^{\text{inter}-s} - \sum_{i=1}^{N} c_{i,h}^{\text{inter}-b} \geq 0. \end{cases} \quad (10)$$

3.2. Stage 2: Cooperative Game Model between Load Aggregator Members. The model calculates the energy price based on the results of stage one and determines the appropriate energy transaction volume and energy price between IES to ensure that each alliance member can make a profit through cooperation while maximizing the benefits of cooperation. It then goes back to stage one for the purchase and sale of energy. Each member must simply inform the other members of its expected volume of energy transactions. Finally, the optimal energy transaction volume for each participant in the multi-IES system that maximizes social benefits is determined, and a community of interests is formed between multiple integrated energy operators and users.

3.2.1. User Model. The utility function is used to evaluate the satisfaction of consumers from a known set of goods. It is an important concept for decision-makers and economists, and utility functions typically use mathematical forms to describe consumer preferences and satisfaction. In this case, the utility of energy users (EU) is defined as the overall satisfaction they obtain from purchasing electricity, heat, and cold energy. The value of this utility function itself has no practical significance. It is only meaningful when compared with other utility functions to evaluate the pros and cons of different energy consumption schemes. Commonly used quadratic functions are often used to represent the utility functions of energy consumption.

3.2.2. User Model Objective Function. As only the IDR is taken into consideration, the amount of energy that the user would consume at each time if there were no demand response is called the user's baseline load. When the user deviates from the baseline load, a satisfaction loss is incurred, which can be quantified by the following function:

$$U_{i,\text{UT}}(t) = \sum_{e\in E}\left[\alpha_{i,j}L_{i,j,R}(t) - \beta_{i,j}L_{i,j,R}^{2}(t)\right], \quad (11)$$

where e is the eth type of energy; E is the set of energy use types of users, E = {ele, heat, cold}; $U_{i,\text{UT}}(t)$ is the energy use utility of users in IESi; $\alpha_{i,j}$ and $\beta_{i,j}$ are the energy use preference constant factor; and $L_{i,j,R}(t)$ is the actual load of energy e in IESi at time t.

Since only the IDR is considered, and the user has the most suitable amount of energy to use at each time, L_B is called the baseline load of the user. When the user deviates from the baseline load, a satisfaction loss is incurred, which is quantified by the following function:

$$U_{i,\text{SL}}(t) = \sum_{e\in E}\left[\frac{1}{2}\lambda_{i,j}\text{DI}_{i,j}^{2}(t) + \theta_{i,j}I_{i,j}(t)\right], \quad (12)$$

where $U_{i,\text{SL}}(t)$ is the satisfaction loss of IESi customers and $\lambda_{i,j}$ and $\theta_{i,j}$ are the satisfaction loss parameters of IESi energy e. $D_{I-i,j}(t)$ is the load adjustment quantity whose value is the difference between the actual load and the baseline load:

$$D_{I-i,j}(t) = \left|L_{i,j,R}(t) - L_{i,j,B}(t)\right|, \quad (13)$$

where $L_{i,j,B}(t)$ is the baseline load of energy e at time t for IESi.

The actual load of the users of the IES can be expressed as

$$\begin{cases} L_{i,\text{ele},R}(t) = L_{i,\text{BE}}(t) + L_{i,\text{EDR,np}}(t) + L_{i,\text{EDR,int}}(t), \\ L_{i,\text{heat},R}(t) = L_{i,\text{BH}}(t) + H_{i,\text{hw}}(t), \\ L_{i,\text{cold},R}(t) = L_{i,\text{BC}}(t) + H_{i,\text{id}}(t), \end{cases} \quad (14)$$

where $L_{i,\text{ele},R}(t)$, $L_{i,\text{heat},R}(t)$, and $L_{i,\text{cold},R}(t)$ are the actual electrical, thermal, and cooling loads of the integrated energy system i at time t and $L_{i,\text{BE}}(t)$, $L_{i,\text{BH}}(t)$, and $L_{i,\text{BC}}(t)$ are the basic electrical, thermal, and cooling loads, respectively.

In summary, the benefit claim of the load within IESi can be expressed as a composite benefit function that maximizes

$$\max U_{i,\text{LA}} = \sum_{t=1}^{T} U_{i,\text{LA}}(t) = \left\{U_{i,\text{UT}}(t) - U_{i,\text{SL}}(t) - \sum_{e\in E}\left[L_{i,e,R}(t)\cdot\gamma_e(t)\right]\right\}, \quad (15)$$

where $U_{i,\text{LA}}$ is the combined benefit of the IESi load and $\gamma_e(t)$ is the price of energy e at moment t. This energy price is set by the multi-IES system and announced to the users.

3.2.3. User Demand Response Constraints

(1) Curtailable electrical loads

Curtailable electrical loads refer to the loads in the IES that can be adjusted, reduced, or controlled based on actual needs. These loads usually include some peakable, controllable, or flexible loads in the IES, such as air conditioners and electric water heaters. By adjusting these loads, the load on the generator can be reduced in case of under- or overload of the power system, thus maintaining the stability and reliability of the power system. The formula for curtailable electrical loads is as follows:

$$0 \le P_{i,t}^{e,\text{cut}} \le \beta_{i,t}^{e,\text{cut}} P_{i,t}^{e,\text{load}}, \tag{16}$$

where $P_{i,t}^{e,\text{cut}}$ and $P_{i,t}^{e,\text{load}}$ are the base load and curtailable load curtailment of the ith IES at time t, respectively, $P_{i,t}^{e,\text{cut}} \ge 0$ indicating that the curtailment is constant positive; and $\beta_{i,t}^{e,\text{cut}}$ is the maximum proportion factor of curtailable load on the demand side.

(2) Transferable electric loads

Transferable electrical loads are the loads in the IES that can be controlled or shifted to achieve power balance during a specific time period. These loads typically include a number of flexibly adjustable electrical demands. By controlling or shifting these loads, their consumption time can be adjusted to the demand of the power system, thus improving the efficiency and stability of the power system. The formula for transferable electrical loads is as follows:

$$\left|P_{i,t}^{e,\text{mov}}\right| \le \beta_{i,t}^{e,\text{mov}} P_{i,t}^{e,\text{load}}, \tag{17}$$

where $P_{i,t}^{e,\text{mov}}$ is the transferable load transfer of the ith IES in time period t, defined $P_{i,t}^{e,\text{mov}} > 0$ as when the transfer is positive and $P_{i,t}^{e,\text{mov}} < 0$ when the transfer is negative; and $\beta_{i,t}^{e,\text{mov}}$ is the proportionality factor of the demand-side transferable load.

$$\sum_{t}^{T} P_{i,t}^{e,\text{mov}} = 0, \tag{18}$$

where T denotes the optimal dispatch cycle, and this equation indicates that the transferable electric load of each IES keeps the total amount constant during the optimal dispatch cycle.

(3) Flexible thermal loads

Flexible thermal loads are thermal loads that can be adjusted, controlled, or moved to suit the demands of the thermal energy system. These loads typically include some thermal energy demand that can be peaked, regulated, or flexibly adjusted, such as water heaters and heating systems. These loads can be adjusted to the demand of the thermal energy system to reduce system waste or improve system efficiency. The flexible thermal load is finely modeled as a hot water load with a certain flexibility space, and the user can accept a comfortable water temperature range of $[T^{h,\text{flex,min}}, T^{h,\text{flex,max}}]$, and the ideal water temperature is $T^{h,\text{flex,set}} = (T^{h,\text{flex,min}} + T^{h,\text{flex,max}}) * 0.5$. So, the flexible thermal load power to maintain the water temperature can also be expressed as an interval. The formula is as follows:

$$\begin{cases} P_{i,t}^{h,\text{flex, min}} = C^W \rho^W V_{i,t}^{\text{cold}} \left(T^{h,\text{flex, min}} - T^{h,\text{flex,ini}}\right), \\ P_{i,t}^{h,\text{flex, max}} = C^W \rho^W V_{i,t}^{\text{cold}} \left(T^{h,\text{flex, max}} - T^{h,\text{flex,imi}}\right), \\ P_{i,t}^{h,\text{flex, min}} \le P_{i,t}^{h,\text{flex}} \le P_{i,t}^{h,\text{flex, max}}, \end{cases} \tag{19}$$

where $P_{i,t}^{h,\text{flex,min}}$ and $P_{i,t}^{h,\text{flex,max}}$ are the ith IES in t time flexible heat load maximum and minimum values, respectively; C^W is the specific heat capacity of water; ρ^W is the density of water; $V_{i,t}^{\text{cold}}$ is t time the ith region needed to heat the volume of cold water; and $T^{h,\text{flex,ini}}$ is the initial water temperature.

(4) Flexible cooling load

Similar to the flexible heat load, the flexible cold load is finely modeled as a chilled water load with a certain flexible space, and the comfortable room temperature range acceptable to the user is $[T^{c,\text{flex,min}}, T^{c,\text{flex,max}}]$, and the ideal indoor temperature is $T^{c,\text{flex,set}} = (T^{c,\text{flex,min}} + T^{c,\text{flex,max}}) * 0.5$. So, the flexible cold load power to maintain the indoor temperature can also be expressed as an interval. The formula is as follows:

$$\begin{aligned} P_{i,t}^{c,\text{flex, min}} &= \frac{n_{i,t}\left(T_{i,t}^{\text{od}} - T^{c,\text{flex, max}}\right)}{R^{id}}, \\ P_{i,t}^{c,\text{flex, max}} &= \frac{n_{i,t}\left(T_{i,t}^{\text{od}} - T^{c,\text{flex, min}}\right)}{R^{id}}, \\ P_{i,t}^{c,\text{flex, min}} &\le P_{i,t}^{c,\text{flex}} \le P_{i,t}^{c,\text{flex, max}}, \end{aligned} \tag{20}$$

where $P_{i,t}^{c,\text{flex,min}}$ and $P_{i,t}^{c,\text{flex,max}}$ are the maximum and minimum values of flexible cold load of the ith IES in time period t, respectively; $n_{i,t}$ and $T_{i,t}^{\text{od}}$ are the number of cooling rooms and outdoor temperature required by the ith IES in time period t, respectively; and R^{id} is the house thermal resistance.

3.3. Algorithm and the Two-Stage Optimization Solution Process

3.3.1. Algorithm and Its Solution Steps. In this paper, improved gray wolf algorithm is used in the first stage. The improved gray wolf algorithm is an optimization algorithm for solving optimization problems based on the social behavior of gray wolves in nature. The gray wolf algorithm is inspired by the collaborative, competitive, and chasing behaviors of individuals in a gray wolf pack and searches for an optimal solution in the problem space by simulating these behaviors. The improved algorithm is based on the traditional gray wolf algorithm and adjusts the position update of the individuals and fitness calculation to improve the performance of the algorithm. Its solution steps are as follows:

Step 1: initialize the population: a certain number of gray wolf individuals are randomly generated as the initial population. Each individual represents a potential solution of the problem.

Step 2: calculate fitness: using the objective function of the problem, calculate the fitness value of each gray wolf individual. The fitness value indicates the quality of the solution, the higher the better.

Step 3: determine the gray wolf rank: based on the fitness value, determine a rank for each individual. Individuals with high fitness values receive higher ranks, and individuals with low fitness values receive lower ranks.

Step 4: select the leader: the gray wolf with the highest fitness is selected as the leader from the population. The solution of the leader is considered as the current optimal solution.

Step 5: position update: for each individual, the position of the individual is adjusted according to the position of the leader and the position of the individual itself through certain update rules. This helps the individual to move towards a better solution.

Step 6: search and optimization: the steps of position update are repeated until the stopping condition is satisfied. In each iteration, the gray wolf individual performs a position update to find a better solution based on the leader's information and its own position.

Step 7: leader update: in each iteration, the leader is reselected based on the updated position of the individual and the fitness value. The leader may be updated to an individual with higher fitness if a better solution is available.

Step 8: termination conditions: the algorithm stops when a predetermined number of iterations is reached, accuracy requirements are met, or other termination conditions are met. At this point, the solution of the leader is considered as the output of the algorithm.

3.3.2. Two-Stage Optimization Solution Process. The multi-IES cooperative operating mode is a cooperative game problem that involves the distribution of individual interests while maximizing the benefits of the cooperative alliance and determining the relationship between the optimal energy trading volume and the energy trading price. In order to preserve the participating entities' information privacy, this paper uses the improved gray wolf algorithm in the first stage and optimises the solution in the second stage. Additionally, the interactive iteration process in the solution fully reflects the game interaction process between multiple entities in practice, which has significant practical significance.

According to the established two-layer optimization model, the upper layer adopts the improved gray wolf algorithm and the lower layer adopts Gurobi's method, and the MATLAB software is used to solve the model optimally. The flow chart of the solution is shown in Figure 4:

4. Calculation Analysis

4.1. Program Analysis. This section simulates three integrated energy systems to verify the rationality of the proposed model. References set simulation parameters. To test the effectiveness of this method, four schemes are set up for comparative analysis, as shown in Table 1:

Based on the data of three areas selected from the test area (industrial area, commercial area, and residential area), this section studies the proposed optimization scheduling strategy of avoiding the hybrid game of integrated energy system. According to the model described in this article, the improved gray wolf algorithm and solver are used to solve the problem, and the optimal scheduling scheme of IES and load aggregater is finally obtained.

4.2. Different Comparative Cases. The optimization results under each scheme are shown in Tables 2 and 3.

Scenarios 1 and 2 are the results of cooperative operation and individual operation of each entity, respectively. In the case of stand-alone operation, taking into account the influence of the cost of laddered carbon trading, and with the same on-grid energy price and generation cost coefficients of the equipment in each time period, the equipment output of each operator is the same in each time period when the revenue of each operator is maximized, but due to the difference in the new energy output of each operator, there is a difference in the final revenue. In cooperative operation, each operator assumes the supply of the respective load, and the performance of the plant is greatly increased to match the requirement of the load, and at the same time, the cost of the plant and the carbon trading cost are also increased, but due to the negotiation of the price of the operator's energy interactions and the price of the customer's energy sales are reasonable, so that the interests of the operator and the customer have been improved.

Tables 2 and 3 show that the benefits of IES 1, 2, and 3 were improved by ¥5132.4, ¥5128.6, and ¥5165.4, respectively, while the total benefits of users were improved by ¥5132.2. Through the game operation, the benefits of each entity were improved, and the comprehensive benefits were improved by approximately ¥19826.2. The benefit improvement of each entity accounted for around 1/4 of the total benefit improvement, indicating that the benefits improved through cooperative operation were equally shared among the four entities, consistent with the theory of the game model itself about benefit distribution. This realization of a multiwin situation for each IES and the users demonstrates the advantages of cooperative operation. Compared with the supply of load by the higher-level network, IES combines relatively low-carbon gas-fired generating units and carbon-free new energy sources, resulting in lower carbon emissions of the multi-IES system, which also reflects the advantage of IES in low carbon compared with traditional energy supply.

When comparing Option 3 with Option 4, both the benefits of each IES and the total combined benefits of users are slightly superior to Option 4, and this makes the total

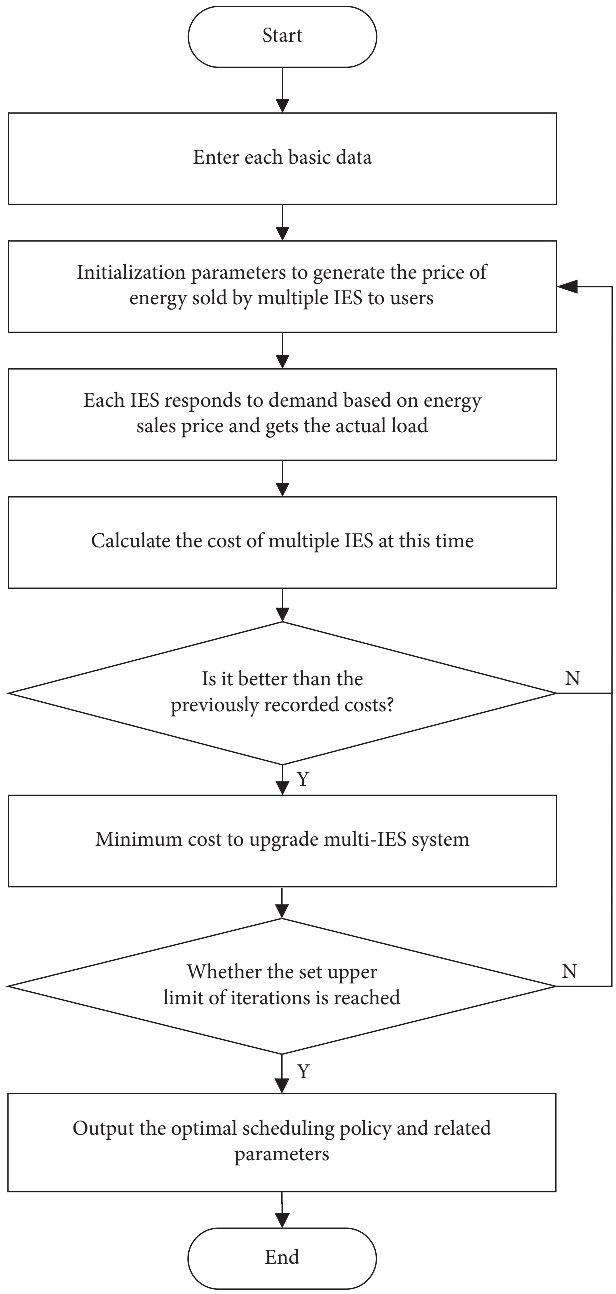

Figure 4: Flow chart of solution.

Table 1: Illustration of different cases.

Scheme	Case study
1	Under the step-by-step carbon trading mechanism, there is energy interaction in multiple IES, and the user's IDR is considered, and the multi-IES-user relationship is established through the game (the scheme of this article)
2	Under the step-by-step carbon trading mechanism, there is no energy interaction in multiple IES, but the user's IDR is considered
3	Under the step-by-step carbon trading mechanism, there is no energy interaction with multiple IES, and the user's IDR and the game relationship with multiple IES are not considered
4	Under the step-by-step carbon trading mechanism, there is energy interaction between multiple IES, but the user's IDR and the game relationship with multiple IES are not considered

Table 2: Operational results under each scenario of the integrated energy system.

Case	IES	Total earnings (Yuan)	Interaction gains with IES (Yuan)	Equipment cost (Yuan)	Interaction with higher-level networks (Yuan)	CO_2 emissions (Kg)	Carbon trading costs (Yuan)
1	1	9952.5	1038.2	3865.9	0	12654.3	315.6
	2	7563.5	−512.6	38719	0	12698.5	319.8
	3	7456.2	−883.4	3882.4	−2.6	12702.9	322.4
2	1	9528.9	0	3758.4	540.3	11448.9	311.4
	2	6785.4	0	4012.5	−895.6	14589.6	901.6
	3	6598.8	0	4026.8	−769.5	16524.8	972.3
3	1	9468.5	0	3699.4	534.6	11408.3	307.9
	2	6089.1	0	3995.8	−905.2	16952.8	985.2
	3	6154.8	0	4006.3	−735.9	17002.9	978.5
4	1	9758.2	1215.3	3967.2	195.8	18103.2	908.9
	2	7059.6	−562.4	4215.6	−31.8	17992.8	854.2
	3	6894.3	−928.1	4295.8	−65.2	18168.9	887.5

Table 3: Operational results under each scenario of the load aggregator.

Case	IES	Energy use utility (Yuan)	Cost of energy use (Yuan)	Comprehensive benefits (Yuan)	Total comprehensive benefits (Yuan)
1	1	53446.0	13787.6	39658.4	71828.4
	2	32625.8	13045.3	19580.5	
	3	26299.0	13709.5	12589.5	
2	1	53110.8	12985.6	40125.2	70976.5
	2	33550.4	13994.2	19556.2	
	3	25448.0	14152.9	11295.1	
3	1	44007.6	14153.9	29853.7	33849.8
	2	20997.6	14145.2	6852.4	
	3	11468.8	14325.1	−2856.3	
4	1	52818.8	13058.9	39759.9	70437.5
	2	33478.0	13895.6	19582.4	
	3	25061.0	13965.8	11095.2	

combined benefits of Option 4 ¥36,587.7 more than that of Option 3. The energy interaction among IESs is considered on the basis of Scenario 3, which makes the total carbon emissions of the multi-IES system decrease.

This indicates that under the stepped carbon trading mechanism, increasing the energy support among IESs can not only increase the benefits of each IES but also achieve the carbon emission reduction. For the users, the total comprehensive benefits are also increased. In fact, the formation of energy interactions among IESs reduces their own various energy supply costs and thus can give more room for benefits to the users, which can be seen from the fact that the total energy costs of users are lower in Scenario 1 than Scenario 2 in Table 3. The comparison between Scenario 1 and Scenario 4 is the result of the game operation before and after considering energy interaction. It can be seen that after the demand response, the benefits of users are greatly improved, and the benefits of each IES are also increased accordingly. In terms of carbon emission, the carbon emission of the multi-IES system is reduced by about 18.9%. After the integrated demand response, the original peak electric load is shifted to the low valley or the time when the new energy generation is sufficient and is supplied by the gas unit and the new energy together at the time of low-carbon emission intensity, while a certain amount of heat load reduced within the comfort level of the customers is a more direct carbon emission reduction measure.

The above analysis shows that not only can the operation of the game increase societal value but also the individual advantages are evident. Increased energy support from operators and integrated demand response from customers can promote the reduction of system carbon emissions. Therefore, the mode of cooperative operation of multiple entities is favorable for the economy and low-carbon operation of the multi-IES system.

4.3. *Analysis of Multi-IES Game Optimization Results*

4.3.1. Algorithm Optimization Results. In the resolution of this thesis, the upper layer system uses the improved gray wolf algorithm to solve and analyse, and the lower layer users use the solver to solve the optimal operation scheme. Considering the two objectives of the IES and the user, the multivariable and the complexity of the scene, in calculating the mechanism to determine the effectiveness of the algorithm, the traditional genetic algorithm, and the improved gray wolf algorithm are used, respectively, and the number of replications is set to 100, and the lowest figure of each generation is logged, and the fitness curve is created, as shown in Figure 5.

The enhanced gray wolf algorithm chosen in this paper is faster in finding the objective solution compared to the traditional genetic algorithm, and the 21st generation reaches convergence to find the objective solution when the number of iterations is set to 100. The classical genetic algorithm has poor performance in convergence and accuracy in finding the solution, converging only 71 times with the setting of 100 iterations and dropping into the local optimum. Therefore, the improved gray wolf algorithm selected in this work is feasible and efficient for solving the dual purpose operation scheduling of IES.

4.3.2. Analysis of Power Optimization Results. The power optimization results of IES1, IES2, and IES3 are shown in Figures 6–8 respectively. Observing Figure 5, it can be found that during 01:00–06:00 and 21:00–24:00, IES1 has a low demand for electric load, and the corresponding power price is low. The rich scenery resources can meet the load supply in most periods, and the area cannot be completely full. Additionally, there is an excess of electricity generated by the gas turbine during this period, so the excess electricity is sold to IES2 and IES3, and the remaining electricity is stored for supply during peak hours. At 01:00–06:00, the electrical load of the three integrated energy systems is at the lowest level throughout the day, while at 15:00–20:00, the electrical load of IES2 and IES3 is at its peak. At this time, it needs to be discharged, and the discharge can maximize the benefits. IES1 does not discharge from 06:00–15:00 because IES2 and IES3 have their own wind power generation during this period. Under the combined action of gas turbine and wind power, they can meet their own electrical load needs. At the same time, the excess electrical energy is supplied to IES1 to alleviate its peak of electric energy stress.

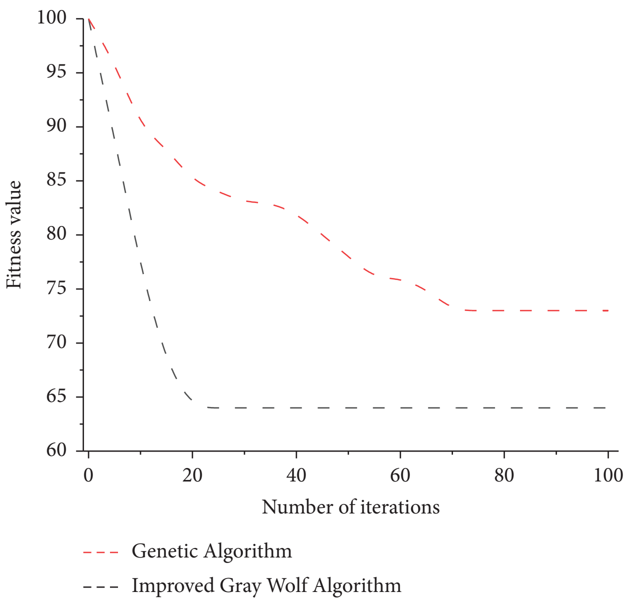

Figure 5: Adaptation curves of different algorithms.

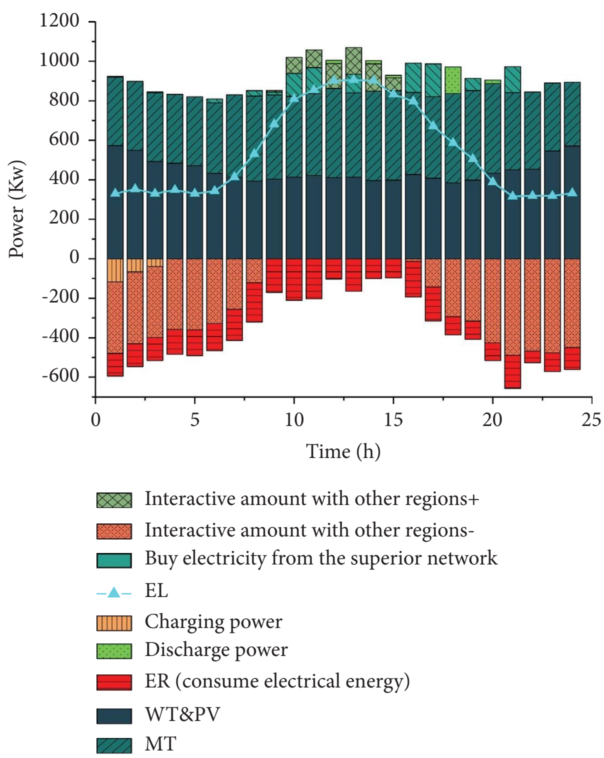

Figure 6: IES1 power optimization.

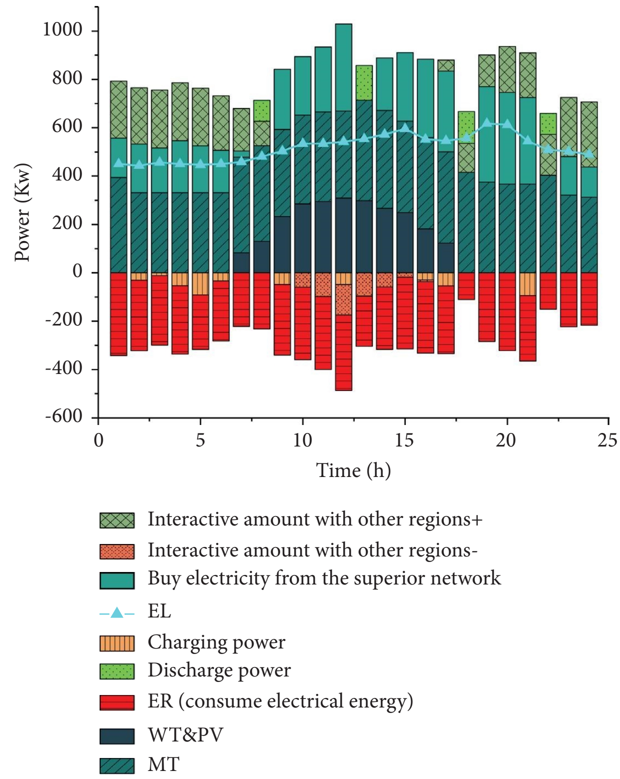

Figure 7: IES2 power optimization.

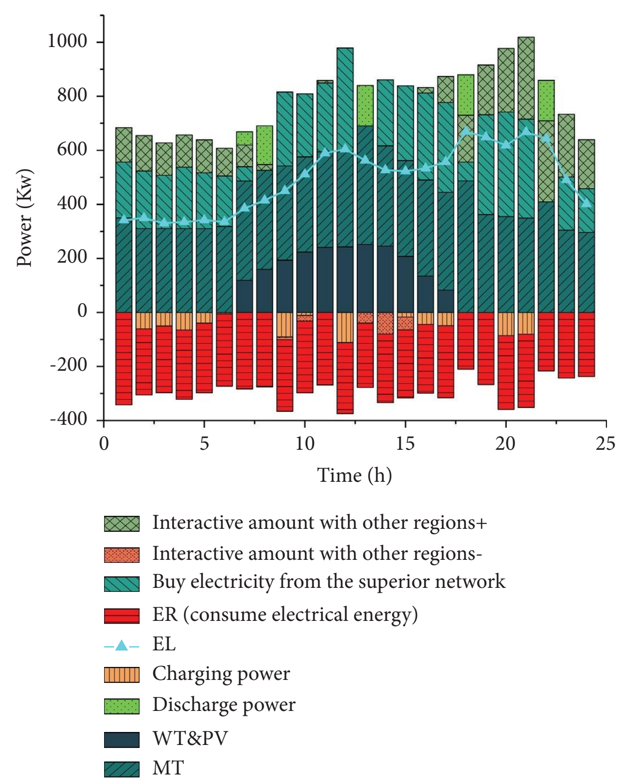

Figure 8: IES3 power optimization.

4.3.3. Analysis of Cold Energy Optimization Results. The cold energy optimization results of IES1, IES2, and IES3 are shown in Figures 9–11, respectively. Looking at Figure 8, it can be found that at 01:00–06:00 and 22:00–24:00, the cold load required by IES1 users is low, and the cold energy generated by wind power and air conditioning can be stored or sold to other IES. At 08:00–22:00, there are a lot of cold loads required by users. At this time, it is necessary to meet the energy demand by purchasing cold energy from other IES. For the cold load demand of IES3, there is less demand during the day and more demand at night. The cold load requirements of all IES2 users are basically the same, and the excess cold energy will be sold to other IES throughout the day.

4.3.4. Analysis of Thermal Energy Optimization Results. The thermal optimization results of IES1, IES2, and IES3 are shown in Figures 12–14, respectively. Observing Figure 11, it can be found that the gas boiler and waste heat boiler of each IES are heated at the same time and have a certain amount of heat energy transmission to other IES under the premise of meeting their own certain heating level. IES1 has a lower demand for heat load at 01:00–06:00 and 22:00–24:00 and higher at 07:00–21:00, while IES3 has a higher demand for heat load at 01:00–08:00 and 18:00–24:00 and lower between 09:00 and 17:00. During 01:00–06:00 and 18:00–24:00, the heat supply pressure of IES1 is small, and heat energy is sold to IES3. In order to relieve the heat supply pressure, IES3 chooses to buy heat energy from IES1. The opposite occurs from 06:00–18:00, where IES3 sells thermal energy and IES1 buys thermal energy. For IES2, there is basically no energy interaction with other operators throughout the day. It only sells heat energy to other operators at a time when the heat supply pressure is not high and buys heat energy from other operators during the peak heat supply.

4.3.5. Analysis of Comprehensive Demand Response Optimization Results. The introduction of IDR in multiple IES helps to reduce energy waste and improve the efficiency of the overall energy system. For users, the user's response enables the system to adjust energy demand during peak and trough times, so as to balance network load, reduce energy waste, reduce network pressure, and improve network stability. Energy consumption can be reduced during peak hours, thus reducing peak electricity prices and dependence on nonrenewable energy, helping to fill the load curve of the power grid and helping to reduce energy consumption during periods of high pollution or high energy consumption, thus reducing carbon emissions and environmental impacts. The user response increases the flexibility of the whole system, makes the energy system more adaptable to the changing energy demand and supply, and helps to promote sustainable development, reduce dependence on limited nonrenewable energy, and improve the long-term sustainability of the overall energy system.

The optimization results of each IES load are shown in Figures 15–17. Looking at Figure 14, it can be found that the electric load after the demand response of IES3 has achieved the effect of cutting peaks and filling valleys, transferring the load of electricity prices in the higher period from 08:00 to 16:00 to other troughs with lower electricity prices, which brings a lot of invisible benefits to multiple IES. For the demand response of heat load and cold load, there is a certain reduction at every moment. After the comprehensive demand response, the users completed the load reduction within the appropriate range, reducing the cost of the user's energy purchase. At the same time, it also alleviated the energy supply pressure of the integrated energy system at peak hours to a certain extent, achieving a win-win situation. The results of the other two integrated energy systems are similar, so they will not be repeated.

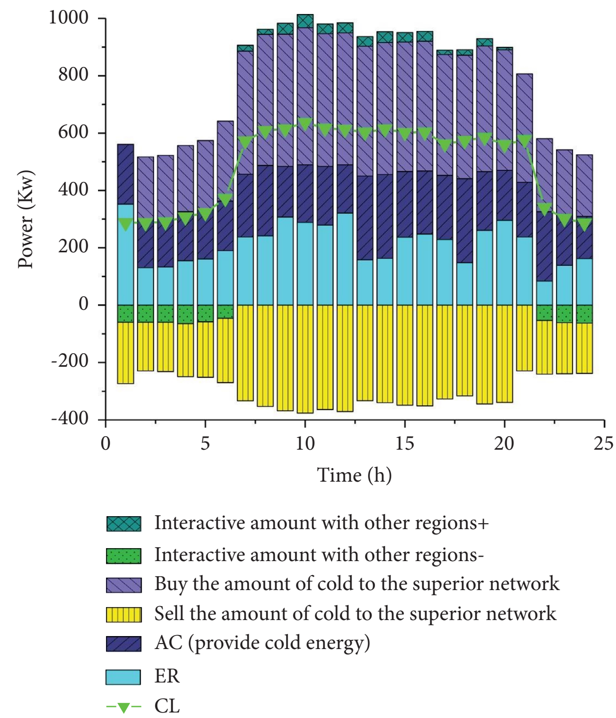

Figure 9: IES1 cold energy optimization.

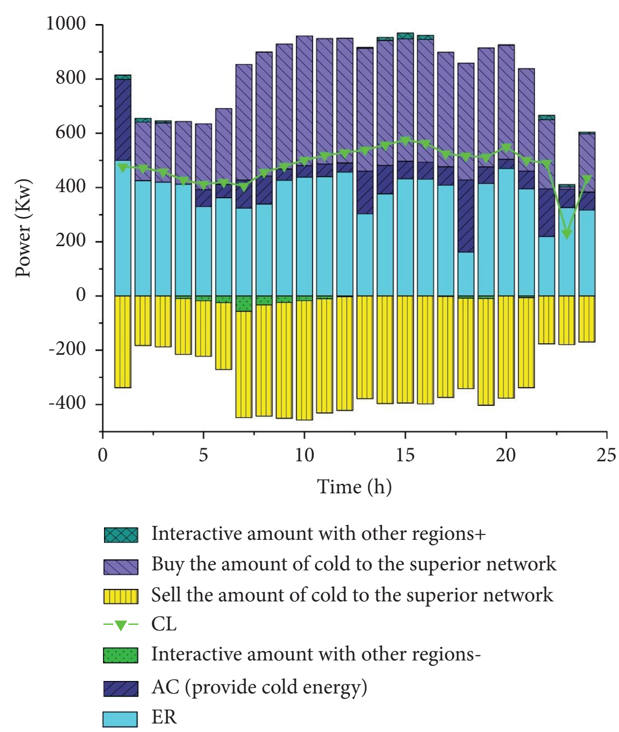

Figure 10: IES2 cold energy optimization.

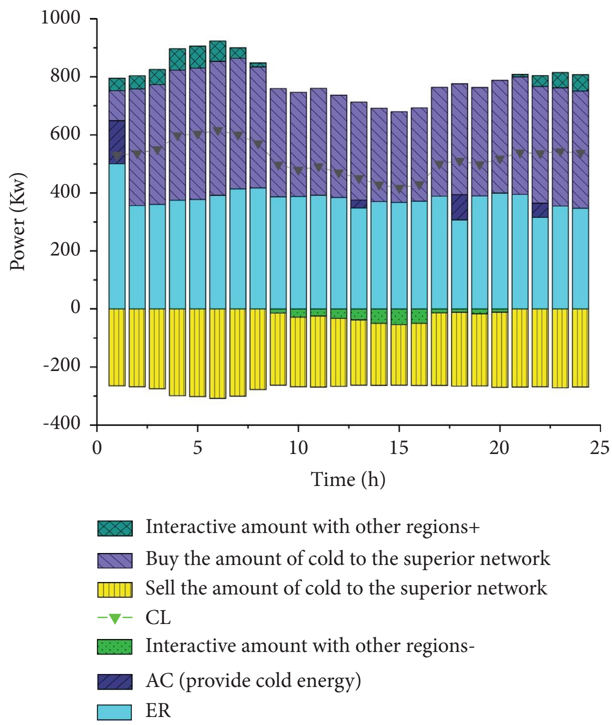

Figure 11: IES3 cold energy optimization.

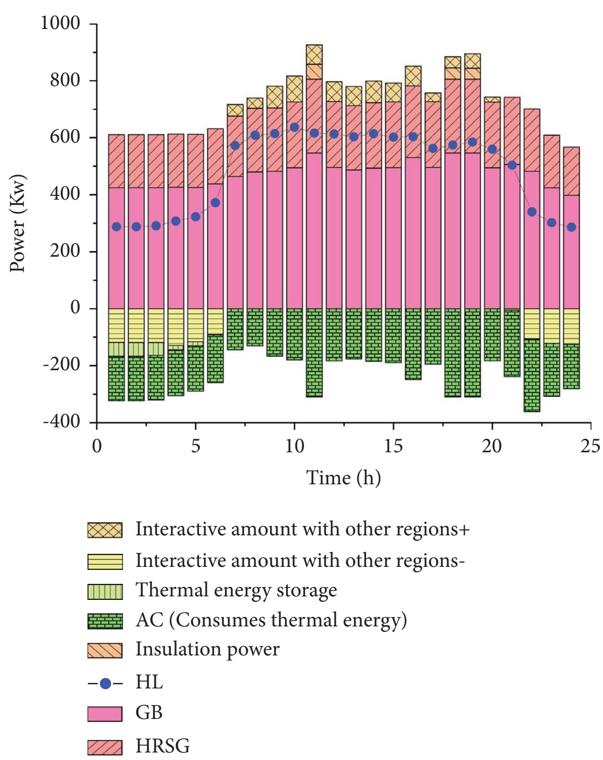

Figure 12: IES1 thermal energy optimization.

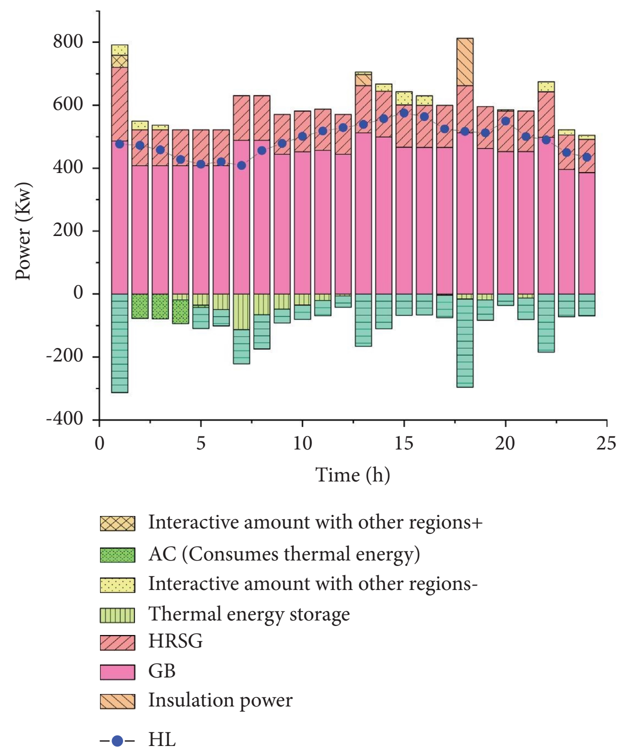

Figure 13: IES2 thermal energy optimization.

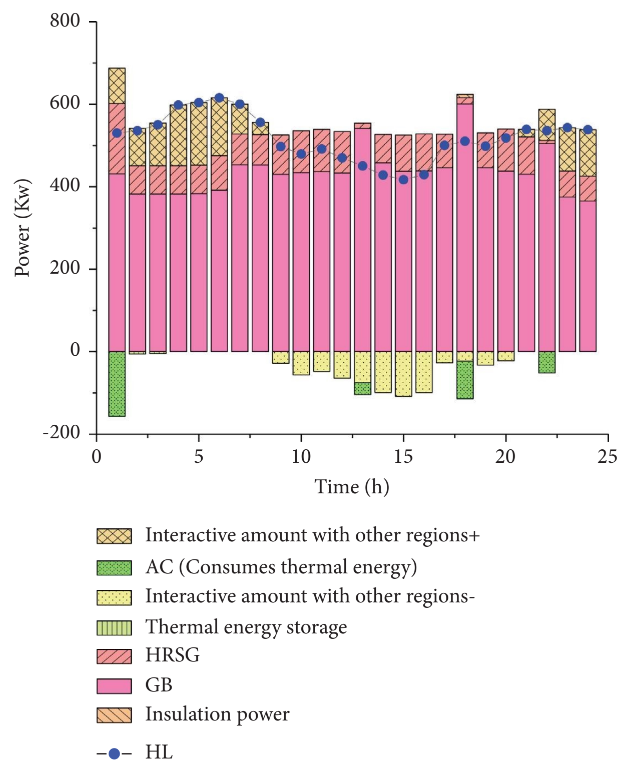

Figure 14: IES3 thermal energy optimization.

4.3.6. Analysis of Energy Price Optimization Results. Figures 18–20 show the energy prices set by bargaining between multiple IES and users in the multi-integrated energy system and between the integrated energy systems. Compared with the energy interaction price between IES and the superior network at each period, it is within the acceptable range of both multiple IES and users. IES can

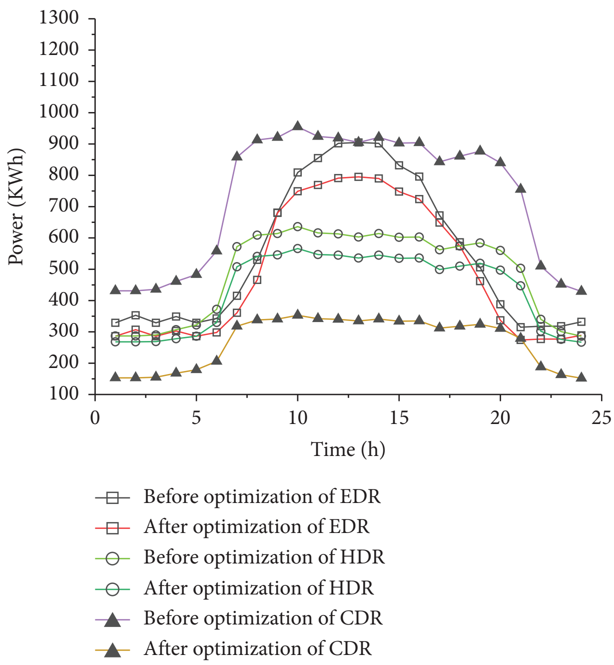

FIGURE 15: Comparison before and after IES1 load optimization.

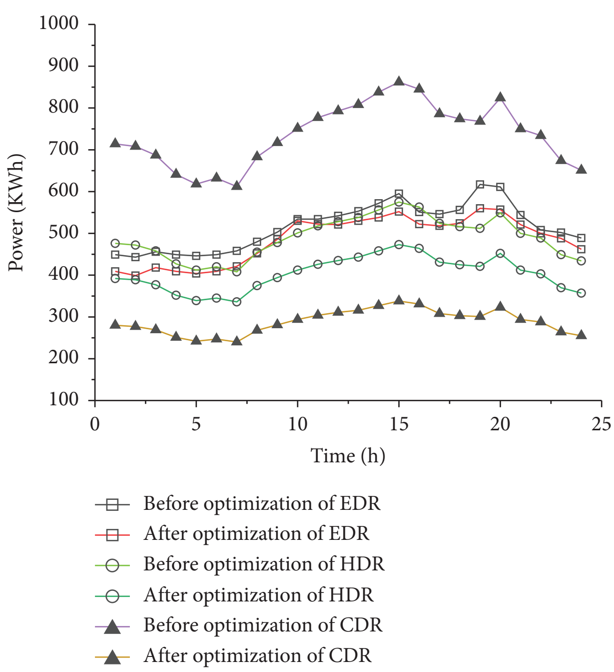

FIGURE 16: Comparison before and after IES2 load optimization.

negotiate for lower energy prices or sell and buy excess energy to achieve the lowest cost and improve their own profits.

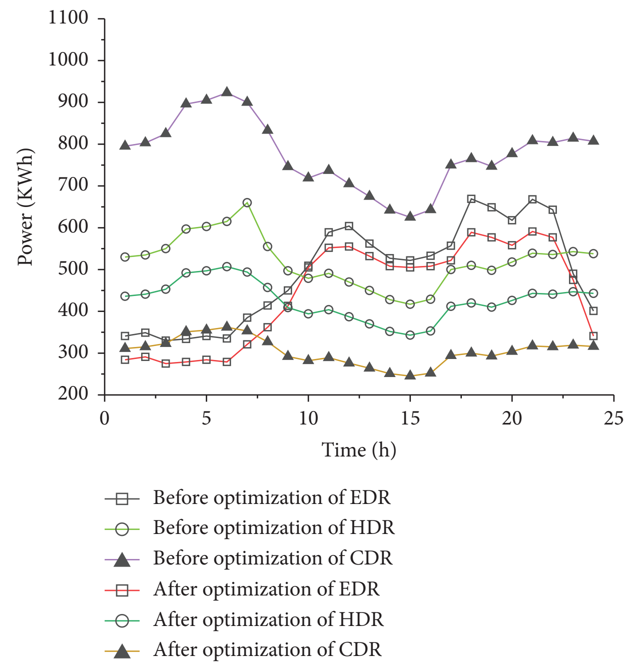

FIGURE 17: Comparison before and after IES3 load optimization.

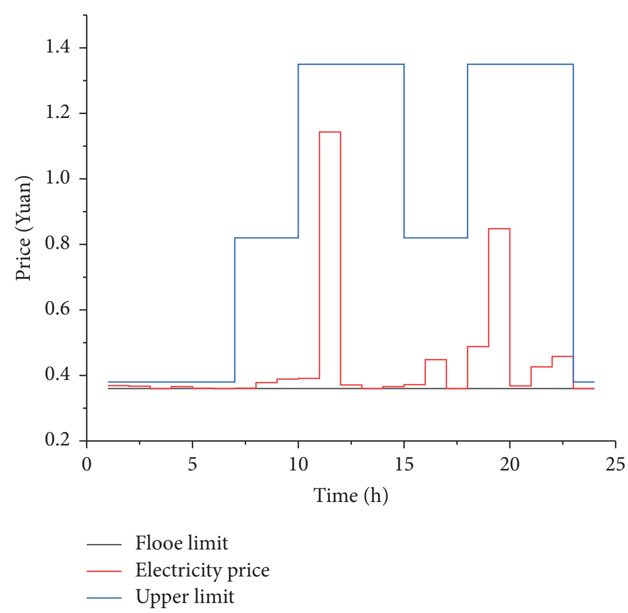

FIGURE 18: Electricity prices.

To sum up, it can be concluded that the introduction of comprehensive demand response and mixed game mechanism can improve the operation economy of multi-IES with electricity, heat, cooling, and gas. It strengthens the energy support of IES between multiple IES, thus

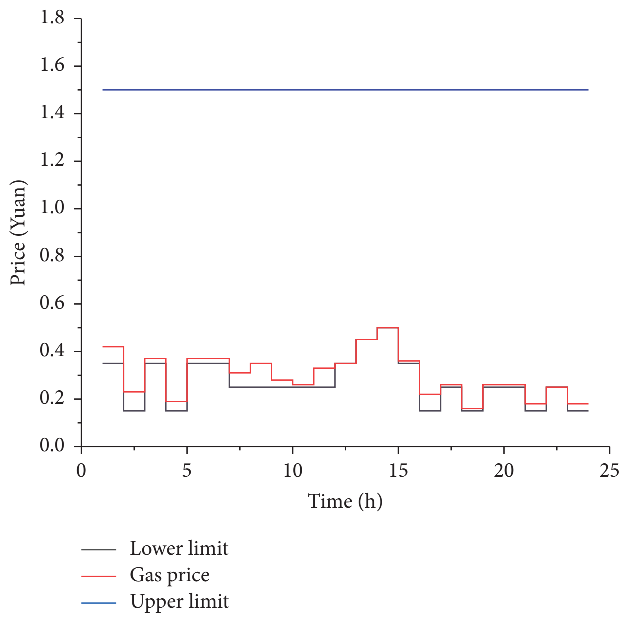

Figure 19: Gas energy prices.

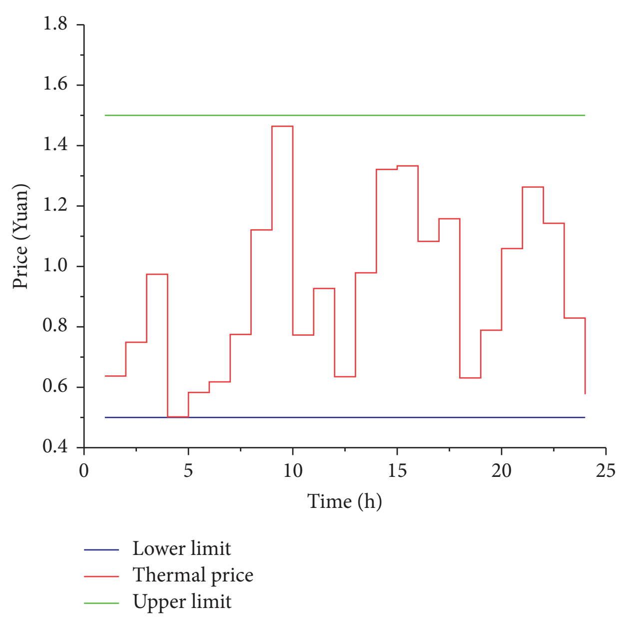

Figure 20: Thermal energy prices.

increasing the use of energy within multiple IES and further improving the economy of multiple IES and user systems.

5. Conclusion

This paper focuses on the multi-IES optimization scheduling under the step-by-step carbon trading mechanism and proposes a hybrid game framework of multi-IES and load aggregator. The improved gray wolf algorithm is used to solve the model. The main conclusions are as follows:

(1) The improved gray wolf algorithm can effectively solve the mixed game model constructed in this article, and the optimization results show that the model established in this article is real and effective.

(2) The hybrid game model constructed in this article can formulate the purchase and sale prices of multiple IES and the energy transaction price between load aggregators and achieve cooperation and revenue distribution between multiple IES while ensuring the coordinated operation of both multiple IES and load aggregators. The constructed model effectively improves the benefits of multiple IES.

(3) The introduction of energy transactions between demand-side response and multi-IES can reduce the operating costs of multi-IES on the basis of the original interaction and reduce the dependence of multi-IES on the superior network.

The comparative analysis of examples shows that the use of mixed games to express the interaction between supply and demand can improve Pareto optimization to a certain extent and improve social benefits. At the same time, under the step-by-step carbon trading mechanism, IES has energy support for other IES, so as to reduce other IES carbon emissions and operating costs and finally achieve the effect of maximizing social benefits and reducing carbon emissions, achieving overall optimization while taking into account the interests of individuals and achieving a fair distribution of benefits.

With the comprehensive development of the carbon trading market and the further opening of the energy market, the strategy proposed in this paper is of certain practical significance to analyse the interest interaction between different decision subjects in the multi-IES under the step-by-step carbon trading mechanism, taking into account the social and individual benefits and achieving the effect of carbon emission reduction. In subsequent research, the effect of uncertainties of new output on the joint operation of multi-integrated energy systems will be studied, and the hybrid game scheduling of several different IES in combination with multiobjective algorithms will be further investigated.

Data Availability

The data used to support the findings of this study are included within the Supplementary Materials.

Conflicts of Interest

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

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Supplementary Materials

See Annex Supplementary Files' Data for the basic data of this paper. (*Supplementary Materials*)

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