Dynamic Pricing and System Optimization of Integrated Energy System in Industrial Parks Based on Carbon Tax

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***Abstract*—Aiming to improve the efficiency of the industry park's integrated energy system and reduce carbon emissions, this paper adopts dynamic pricing and carbon tax mechanisms. Utilizing game theory, a leader-follower game framework is constructed with the energy system operator (ESO) as the leader and building users as followers. Through the integration of dynamic pricing and carbon tax model, the paper demonstrates notable improvements in economic and low-carbon performance within the energy system. Consequently, in this paper, it provides valuable support for sustainable energy development and economic operations in a low-carbon economy. The findings underscore the potential of dynamic pricing and carbon tax mechanisms as integral contributors to achieving a more sustainable and economically efficient energy landscape.**

***Index Terms*--Carbon Tax, Demand Response, Differential Evolution Algorithm, Dynamic Electricity Prices, Leader-follower Game**

I. Introduction

Energy plays a pivotal role in driving modern societal development, offering avenues for enhancing efficiency, reducing costs, and fostering the adoption of clean energy solutions through comprehensive energy systems [1]-[3]. As urbanization accelerates and environmental concerns take center stage, park-level comprehensive energy systems have emerged as a focal point for efficient energy supply and management [4]. However, traditional dynamic pricing mechanisms within these systems face challenges such as price fluctuations and limited adaptability [5]-[7], necessitating exploration into innovative approaches like game theory to enhance their effectiveness.

Scholars have extensively researched optimal planning schemes for comprehensive energy systems, focusing on economic efficiency, reliability, and the promotion of renewable energy consumption. Among these efforts, demand response (DR) has gained traction as a solution for smart grid utilization. Integrated Demand Response (IDR) strategies leverage demand-side resources for flexible adjustments. Reference [8] developed optimization and scheduling models for comprehensive energy systems with carbon capture systems, employing a leader-follower game framework. References [9]-[10] proposed low-carbon optimization strategies for integrated energy systems, incorporating tiered carbon trading mechanisms and comprehensive demand response strategies. Reference [11] introduced a Stackelberg leader-follower game model to optimize industrial park comprehensive energy systems, integrating economic operation and auxiliary services. Reference [12] established a leader-follower game model for optimizing power company park integrated energy systems (PIES), addressing equilibrium strategy problems between PIES, power companies, and users. Reference [13] proposed a multi-party energy management framework for combined heat and power (CHP) systems, incorporating power and thermal demand response.

Carbon trading and carbon taxes are recognized as effective means to promote low-carbon operations [14]. Research [15] presents optimization models incorporating carbon taxes, showing improved performance compared to reference systems. Research [16]-[17] determines optimal renewable energy subsidies and establishes energy-carbon prices, enhancing low-carbon operation. Research [18] introduces a hybrid carbon tax in an operator-user game model, reducing system emissions and user energy costs. Additionally, research [19] proposes coordinated optimization strategies considering carbon quotas and integrated demand response, offering dual incentives for comprehensive energy systems.

However, while these studies have delved into various aspects of comprehensive energy systems optimization, there is a notable gap in understanding the integration of carbon tax mechanisms into integrated energy systems. In this context, this paper aims to explore the potential of integrating carbon tax mechanisms into park-level integrated energy systems to improve energy utilization efficiency and reduce carbon emissions. By leveraging insights from game theory and building upon existing literature on energy system optimization, this paper seeks to develop more flexible and efficient pricing mechanisms that integrate carbon tax, thereby contributing to both theoretical understanding and practical implementation in energy system management.

II. Model Construction

A. Energy Trading Framework

In the electricity market, the energy system operator (ESO) and PIES play pivotal roles, and their autonomous decision-making profoundly impacts each other and the market.

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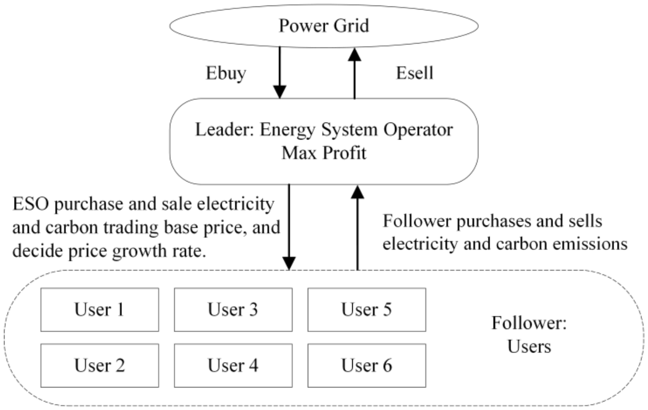

Figure 1. Energy trading framework

ESO, as the leader, sets time-based electricity pricing and grid access fees, aiming to maximize economic interests by considering electricity purchase demands and carbon emissions. ESO profits through transactions with the grid and industry parks.

Users, as followers, respond to ESO's pricing strategy, factoring in variables like carbon tax prices. Their decisions influence ESO, which adjusts its strategies to meet market demands and optimize profitability.

This dynamic interaction forms a leader-follower game framework with ESO as the leader and users as followers in Fig.1. They mutually influence each other, shaping the electricity market's operation. The complexity of this framework requires adaptability to evolving market dynamics and demands.

B. Profit Model of ESO

The objective function is a critical component of the system's dynamic pricing model based on leader-follower game theory, playing a significant role in the study. This paper aims to achieve the efficient utilization of PIES and a reduction in carbon emissions through this model. Therefore, in setting the objective function, it is necessary to consider three aspects: supply-demand equilibrium, energy efficiency, and carbon emission control.

$$\max F_{ESO} = \sum_{t=1}^{T}(I_{sell}(t) - C_{buy}(t) - C_{Rm}(t)) - \gamma(\sum_{i=1} C_{i,PIES} - \bar{C}) \quad (1)$$

Where F_{ESO} represents the total profit of ESO; $I_{sell}(t)$ represents the sales electricity revenue of ESO at time t; $C_{buy}(t)$ is the energy purchase cost of ESO at time *t*; $C_{Rm}(t)$ represents the operating cost of ESO at time *t*. $C_{i,PIES}$ is the actual carbon energy emissions of the *i*-th user. γ is the carbon penalty coefficient. $\bar{C}$ is the carbon emission threshold set by the government, and if it exceeds, a certain penalty will be imposed.

$$I_{sell}(t) = \sum_{i=1}^{n} A_{i.s}(t)\,\pi_s^e(t) + A_{sw}(t)\pi_{sw}(t) \quad (2)$$

$$C_{buy}(t) = C_{grid}(t) + C_{PIES}(t) \quad (3)$$

$$C_{Rm}(t) = C_{mt}(t) + C_{pv}(t) + C_{wt}(t) \quad (4)$$

Where in:

$$C_{grid}(t) = A_{fs}(t)\pi_{fs}(t) \quad (5)$$

$$C_{PIES}(t) = \sum_{i=1}^{n} A_{i,b}(t)\pi_b^e(t) \quad (6)$$

$$C_{mt}(t) = P_{mt}(t) * K_{MT} \quad (7)$$

$$C_{pv}(t) = P_{pv}(t) * K_{PV} \quad (8)$$

$$C_{wt}(t) = P_{wt}(t) * K_{PW} \quad (9)$$

Where $\pi_s^e(t)$, $\pi_{sw}(t)$ is the price at which ESO sells and purchases electricity from users at time *t*;$\pi_{fs}(t)$, $\pi_{sw}(t)$ is time-of-use electricity price and the on-grid electricity price of the power grid at time *t*; $A_{i.s}(t)$ is the amount of electricity sold by ESO to users at time *t*.

$C_{grid}(t)$, $C_{PIES}(t)$is the cost of purchasing energy from the superior power grid and park by ESO at time *t*;$\mathrm{A_{sw}(t)}$, $\mathrm{A_{sw}(t)}$ is the amount of electricity purchased and sold by ESO from the superior power grid at time *t*; $A_{i,b}(t)$ is the amount of electricity purchased by ESO from the *i*-th user at time *t*.

$C_{Rm}(t)$ is the operation and maintenance cost. $C_{MT}(t)$, $C_{PV}(t)$, $C_{PW}(t)$ represents the operation and maintenance costs of gas turbines, photovoltaic motors, and wind turbines; $P_{mt}(t)$, $P_{pv}(t)$, $P_{wt}(t)$ represents the operating power of gas turbines, photovoltaic motors, and wind turbines; K_{MT}, K_{PV}, K_{PW} is the operation and maintenance constant for gas turbines, photovoltaic motors, and wind turbines.

C. Constraint Condition

1) Restrictions on Purchasing and Selling Electricity

To ensure that each entity does not directly engage in transactions across operators or with the outside world, restrictions should be placed on the seller's quotation to ensure that the buying and selling prices are within the market price range of electric thermal energy, expressed as:

$$P_{gridmin} \le P_{grid}(t) \le P_{gridmax} \quad (10)$$

$$0 \le P_{grid\_buy}(t) \le P_{gridmax} \quad (11)$$

$$P_{gridmin} \le P_{grid\_sell}(t) \le 0 \quad (12)$$

Where $P_{grid\_buy}(t)$ and $P_{grid\_sell}(t)$ are the prices at which the seller purchases and sells electricity, respectively $P_{gridmin}$ and $P_{gridmax}$ are the time of use electricity price and grid electricity price of the power grid, respectively.

2) Energy Storage Constraints

Electric energy storage constraints:

$$SOC_e(t) = SOC_e(t-1) + (P_{ch}(t) * e_{ch} - P_{disch}(t)/e_{disch}/E_{sto\_max}) \quad (13)$$

$$SOC_{e,min} \le SOC_e(t) \le SOC_{e,max} \quad (14)$$

Power constraint:

$$0 \le P_{ch}(t) \le \gamma_{ch} P_{ch,max} \quad (15)$$

$$0 \le P_{disch}(t) \le \gamma_{disch} P_{disch,max} \quad (16)$$

State constraint:

$$P_{ch\_bin}(t) + P_{disch\_bin}(t) = 1 \quad (17)$$

Where $SOC_e(t)$ is real-time storage capacity at time t; e_{ch} and e_{disch} represent the charging and discharging efficiency of electrical energy; $SOC_{e,min}$, $SOC_{e,max}$ represents the minimum and maximum storage capacity, respectively; $P_{ch,max}$ and $P_{disch,max}$ are the maximum charging and discharging power; $P_{ch\_bin}(t)$ and $P_{disch\_bin}(t)$ is a binary variable that ensures that the charging and discharging processes do not occur at the same time.

3) Gas Turbine Constraints

Micro gas turbines recover the waste heat from high-temperature flue gas and provide heating power. The operational constraints of micro gas turbines mainly include the upper and lower limits of output. Only the upper and lower limits of output and climbing speed of micro gas turbines are considered.

Gas turbine fuel cost:

$$F_{MT}(t) = a_{MT}(t)P_{MT}(t) + b_{MT} \tag{18}$$

Climbing constraints for gas turbines:

$$\gamma_{\zeta,min} \le P_{MT}(t) - P_{MT}(t-1) \le \gamma_{\mu,min} \tag{19}$$

Gas turbine upper and lower limits:

$$P_{MT,min} \le P_{MT}(t) \le P_{MT,max} \tag{20}$$

Where $P_{MT,min}$ and $P_{MT,max}$ is the lower limit and upper limit of active output for gas turbine units; $P_{MT}(t)$ is the active output of the gas turbine during the time period; $\gamma_{\zeta,min}$ and $\gamma_{\mu,min}$ are the uphill and downhill power limits of the gas turbine; $a_{MT}(t)$ is a coefficient that represents the impact of $P_{MT}(t)$, that is, the degree of impact of $P_{MT}(t)$; b_{MT} is a constant term that represents other factors that affect fuel costs besides active output, such as fixed costs, equipment costs.

4) Power Balance Constraints

In the operation, the total power generation and power load must be balanced, as shown in the equation. The user load must be balanced with the output of distributed energy.

$$P_{wt}(t) + P_{pv}(t) + P_{grid}(t) + P_{MT}(t) + P_{discharge}(t) = e_{load}(t) + P_{charge}(t) \tag{21}$$

Where $e_{load}(t)$ is the electrical load reported by the user.

5) Power Generation Constraints of Wind and Solar Power Generation

$$0 \le P_{wt}(t) \le P_{wt}^{s}(t) \tag{22}$$

$$0 \le P_{pv}(t) \le P_{pv}^{s}(t) \tag{23}$$

Where $P_{wt}(t)$, $P_{wt}^{s}(t)$ represents the actual and predicted output of wind power during the time period; $P_{pv}(t)$, $P_{pv}^{s}(t)$ is the actual and predicted output of the photovoltaic system during the time period.

D. Profit Model of the Building Users

The cost of an individual user consists of utility profit, expenditures of purchasing electricity/heat, and comfortable degree for thermal dissatisfaction, which could be defined as:

$$F_{PIES}(t) = k_i * \ln(1 + e_{load}(t)) - p_{sell} * e_{load}(t) \tag{24}$$

Where $k_i * \ln(1 + el_i^h)$ is the utility that the building users i achieve from consuming energy el_i^h ; k_i is the preference parameter. Normally, the building users' comfortable degree will be reduced by adjusting their door temperatures under DR. However, for the economic reason, as long as the discomfort could be counterbalanced by economic benefits, the users would be willing to participate in the DR. In this paper, the value of k_i is 100.

E. Carbon Tax Model

1) Traditional Carbon Tax Model

Carbon tax is a tax measure implemented by the government on carbon emissions, aiming to internalize the external costs of carbon emissions on the environment and society. This tax is typically based on energy production, consumption or emissions and is levied on a unit of carbon emissions. By taxing carbon emissions, the government can create economic incentives to encourage businesses and individuals to take measures to reduce carbon emissions, and promote the development and application of clean energy and low-carbon technologies. The carbon surcharge is seen as an effective economic tool.

The calculation criteria for ordinary carbon taxes are usually based on the carbon content of emissions and the tax rate. Generally speaking, the calculation formula can be expressed as:

$$C_{CO2} = c(E_p - E_c) \tag{25}$$

Where C_{CO2} is the carbon tax cost; c is the carbon tax price of the current year's carbon tax; E_c is initial free carbon emission quota; E_p is the total carbon emissions of the system.

Therefore, in the actual carbon emission model, the absorbed CO_2 is treated, and the specific conversion process of the carbon emission model is shown in the equation:

$$C_{CO2} = C_{buy} + C_{GT} + C_{GB} \tag{26}$$

$$C_{buy} = X_e \sum_{t=1}^{T} P_{i,s}(t) \tag{27}$$

$$C_{GT} = X_h \sum_{t=1}^{T} (\lambda P_{i,GT}(t) + H_{i,GT}(t)) \tag{28}$$

$$C_{GB} = X_h \sum_{t=1}^{T} H_{i,GB}(t) \tag{29}$$

Where C_{buy}, C_{GT}, C_{GB} respectively, are the actual carbon emissions of users purchasing electricity from ESO, gas turbines, and gas boilers; X_h. X_e is the actual carbon emission coefficient of the unit electric power produced by coal-fired units and the unit thermal power produced by natural gas units.

2) Tiered Carbon Tax Model

Tiered Carbon Tax is a variant that sets different tax rates according to different levels of carbon emissions, usually based on the tiered classification of emissions. In a laddered carbon tax, multiple emission ladders are usually set, with each ladder corresponding to a different tax rate. The specific carbon emission cost range can be divided as follows:

$$C_{CO2}=\begin{cases}-c(1+2\lambda)(E_c-\nu-E_p), & E_p\le E_c-\nu\\ -c(1+2\lambda)\nu-c(1+\lambda)(E_c-E_p), & E_c-\nu\le E_p\le E_c\\ c(E_c-E_p), & E_c\le E_p\le E_c+\nu\\ c\nu+c(1+\alpha)(E_p-E_c-\nu), & E_c+\nu\le E_p\le E_c+2\nu\\ c(2+\alpha)\nu+c(1+2\alpha)(E_p-E_c-2\nu), & E_c+2\nu\le E_p\le E_c+3\nu\\ c(3+\alpha)\nu+c(1+3\alpha)(E_p-E_c-3\nu), & E_c+3\nu\le E_p\le E_c+4\nu\\ c(4+\alpha)\nu+c(1+4\alpha)(E_p-E_c-4\nu), & E_c+4\nu\le E_p\end{cases} \quad (30)$$

Where ν represents the length of the carbon emission interval; λ , α is the reward coefficient and punishment coefficient.

III. Algorithm Framework

A. The Leader-follower Game Framework

In the interaction process of the game, there are two main entities: ESO and PIES. The internal connection between them is established through the price information released by ESO to PIES and the optimization results within PIES. As the leader, ESO first sets the electricity purchase and sale prices, the carbon trading base price, and the rate of price increase, then communicates this information to the follower, PIES. PIES optimizes its equipment output and performs demand response based on the received price information, and then sends the purchase and sale volume information back to the leader. Since carbon emissions cannot be predicted in advance, this paper does not consider dynamic changes to the interval length. The leader, ESO, continuously optimizes the price strategy based on the information provided by the follower, PIES. Due to the sequential decision-making of ESO and PIES, a leader-follower game framework is formed, with ESO as the leader and PIES as the follower. This leader-follower game model can be represented as:

$$G=\left\{\begin{matrix}\{ESO,PIES\};\{\pi_s^e,\pi_b^e,A_{i,s},A_{i,b}\}\\ \{maxF_{ESO},minF_{PIES}\}\end{matrix}\right\} \quad (31)$$

The model comprises the participants of the game, specifically ESO and PIES; the strategy sets of both parties, which include the electricity purchase and sale prices π_s^e and π_b^e determined by the leader ESO; the purchase and sale electricity volumes $A_{i,s}$ and $A_{i,b}$ provided by *i*-th PIES to ESO; and the utilities of both parties, represented by their respective objective functions. The proof of the existence and uniqueness of the game equilibrium is shown in Appendix A.

B. Game Solving Algorithms

This article is based on the MATLAB platform to simulate and implement a comprehensive energy system in the industrial park and uses differential evolution algorithm combined with CPLEX solver to solve the established multi-agent leader-follower game model. The solution flow chart is shown in Appendix B Fig.B1.

IV. Example Analysis

A. Basic Data

Taking an industrial park in northern China as a calculation example, the PIES optimization operation strategy proposed in this article is simulated and analyzed, the operation period is 24 hours, and the scheduling interval is an hour. There are two generators and one gas distribution station.

TABLE I. Total expenditure and carbon emissions

	Case 1	Case 2	Case 3	Case 4
Total Cost (CNY)	15716.44	14391.8	14295.18	14727.77
Maintenance Cost (CNY)	1975.82	1975.82	1874.72	1821.14
Natural Gas Cost (CNY)	3767.45	3767.45	3558.74	3455.86
Electricity Selling Cost (CNY)	0	-521.44	-286.74	-224.02
Electricity Purchase Cost (CNY)	6314.14	5510.94	5694.56	5731.5
Carbon Emission Cost (CNY)	1920.23	1920.23	1805.82	1983.29
MT Unit Carbon Emission Cost (CNY)	1738.8	1738.8	1648.08	1960
Total Carbon Emissions (kg)	26114.04	24905.3	24642.46	24586.42

The park service providers include CHP, photovoltaic power generation systems, and wind turbines. The typical day wind power and photovoltaic prediction curves are shown in Fig.C1. The daily electric load curves of these buildings are shown in Fig.C2. The proportion of maximum shiftable electric loads is set to nearly 20%.

The prices of electricity and gas purchased from the power grid and gas grid are shown in Table II. The basic parameters of the gas turbine are shown in Table III. Other specific parameters are set in [20].

B. Scheme Designs

Based on the above data, the incomplete information game and mixed integer nonlinear model solver are used to solve the optimal dispatching results of the multi-energy collection system. In order to illustrate the rationality of the optimized scheduling model built, this article will compare and analyze the scheduling results of the four models:

Case 1: Without considering dynamic electricity prices and carbon tax.

Case 2: Considering dynamic electricity prices, but do not consider carbon tax.

Case 3: Considering dynamic electricity prices and use the traditional carbon tax mechanisms.

Case 4: Considering dynamic electricity prices and use the tiered carbon tax mechanism.

Taking each model as one-time as an example for analysis, the scheduling results are as TABLE I.

Based on TABLE I, we conducted an analysis of the scheduling results for each scenario. Firstly, in Case 1, the total cost is the highest and the carbon emissions are the largest. This is attributed to the absence of considerations for dynamic electricity prices and carbon tax. In contrast, Case 2, which considers dynamic electricity prices, exhibits reduced total cost and carbon emissions, at 14391.8 CNY and 24905.3 kg, respectively. In Case 3, the incorporation of dynamic electricity prices and traditional carbon tax mechanisms further decreases the total cost and carbon emissions to 14295.18 CNY and 24642.46 kg, respectively which reduce 262.84kg CO_2. Specifically, the use of the traditional carbon tax mechanism reduces carbon tax costs to 1805.82 CNY, compared to Case 1. Lastly, Case 4 integrates dynamic electricity prices with tiered carbon tax mechanisms, resulting in a slightly higher total cost of 14727.77 CNY but the lowest

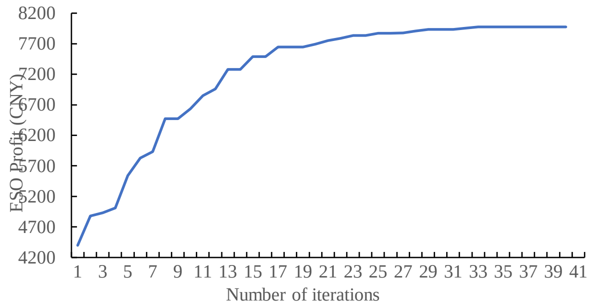

Figure 2. Changes in ESO revenue for Case 3

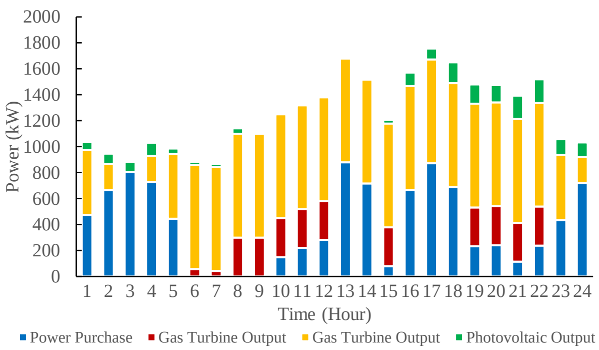

Figure 3. Power load scheduling results for Case 3

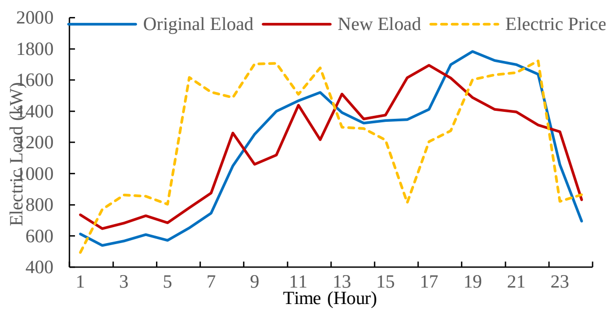

Figure 4. Electric load curve before and after dispatch for Case 3

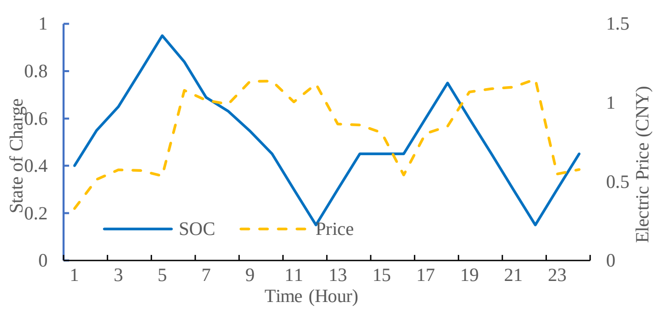

Figure 5. Charging and discharging situation of the battery varies with the electricity price for Case 3

carbon emissions of 24586.42kg, which reduce 56.04kg carbon emission compared with Case 3.

The specific data analysis demonstrates the effectiveness of considering dynamic electricity prices and carbon tax in reducing total costs and carbon emissions. In practical applications, it is crucial to consider both economic costs and environmental impacts to select the optimal scheduling strategy, which may involve further optimization of carbon tax strategies or adjustments to energy usage plans based on Case 4.

In conclusion, the leader-follower game scenario involving demand response and carbon tax mechanism with dynamic parameters benefits ESO and reduces costs for the PIES. It also achieves lower total carbon emissions, showing superior economic and low-carbon performance.

C. Analysis of Optimization Results

The optimization iteration process of ESO is shown in Fig.2. At the 30th iteration, the results have converged. It can be seen from the figure that the method used in this paper has a good convergence effect. When the Stackelberg equilibrium is reached, its strategy no longer changes, which means that under this strategy, no player can obtain more benefits by independently changing his strategy.

The results in Fig.3 indicate that new energy power generation has been fully utilized, improving the justification rate of new energy power generation.

The user energy consumption strategy formulated by the follower based on the energy sales strategy and equipment operating status of the leader ESO and the load curve before and after optimization are shown in Fig.4. Under the incentive of electricity prices, in order to reduce energy expenditures, users reduce electricity consumption and interrupt part of the electricity load during the peak periods of 9:00-11:00 and 20:00-22:00 due to high electricity prices. The peak value of electricity load decreases; during the trough period from 00:00 to 06:00, due to low electricity prices, as shown in Fig.5, users use battery charging to increase electricity consumption, and the user load valley value increases. Before and after optimization, the user's electric load curve shows obvious "peak shaving and valley filling" characteristics, which shows that the operation strategy proposed can effectively reduce the user's energy cost.

The simulation results show that the proposed game interaction model has good convergence, and ESO can better adjust the operation of its distributed energy equipment and purchase energy at a lower cost through game interaction with the user side.

V. Conclusion

This paper explores dynamic pricing in park integrated energy systems, integrating it with carbon tax. A comprehensive overview of these systems and game theory concepts is provided. The introduced dynamic pricing mechanism demonstrates notable advantages in improving energy efficiency and reducing carbon emissions. Combining carbon tax and stepped carbon tax further enhances carbon reduction and sustains energy system sustainability. Overall, this integrated approach offers a promising pathway for achieving sustainable energy development and a low-carbon economy.

VI. APPENDIX

A. *The Existence and Uniqueness of Game Equilibrium*

The reference [21] for proving the existence and uniqueness of game equilibrium is as follows:

Theorem 1: When the master-slave game model satisfies the following conditions, there is a unique Stackelberg equilibrium:

1) The utility function of game participants is a non-empty, continuous function about the game strategy set.

2)The follower utility function is a continuous concave/ convex function with respect to the respective game strategy set.

According to the model proposed in this article, it can be seen that the strategy set needs to satisfy the constraints (10)-(23). Therefore, the strategy sets of both the leader and the participant are non-empty and continuous. Calculate the second-order partial derivatives of a and b respectively for the PIES objective function (24):

$$\frac{\partial^2 F_{PIES}}{\partial^2 A_{i,s}(t)^2} = 0 \quad \text{(A1)}$$

$$\frac{\partial^2 F_{PIES}}{\partial^2 A_{i,b}(t)^2} = 0 \quad \text{(A2)}$$

It can be seen from the above formula that the PIES objective function formula is a linear function about its policy set $A_{i,s}(t)$ and $A_{i,b}(t)$. According to the definition of concavity, the linear function is both a concave function and a convex function.

In the game, when neither the leader nor the follower can achieve greater benefits by altering their own strategies, the game reaches a Stackelberg equilibrium, which can be defined as follows:

$$\begin{aligned}
&F_{ESO}(\pi_s^{e^*}, \pi_b^{e^*}, P_{CHP}^*, P_{MT}^*, DR^*) \ge F_{ESO}(\pi_s^{e}, \pi_b^{e^*}, P_{CHP}^*, P_{MT}^*, DR^*)\\
&F_{ESO}(\pi_s^{e^*}, \pi_b^{e^*}, P_{CHP}^*, P_{MT}^*, DR^*) \ge F_{ESO}(\pi_s^{e^*}, \pi_b^{e}, P_{CHP}^*, P_{MT}^*, DR^*)\\
&F_{ESO}(\pi_s^{e^*}, \pi_b^{e^*}, P_{CHP}^*, P_{MT}^*, DR^*) \ge F_{ESO}(\pi_s^{e^*}, \pi_b^{e^*}, P_{CHP}, P_{MT}^*, DR^*)\\
&F_{ESO}(\pi_s^{e^*}, \pi_b^{e^*}, P_{CHP}^*, P_{MT}^*, DR^*) \ge F_{ESO}(\pi_s^{e^*}, \pi_b^{e^*}, P_{CHP}^*, P_{MT}, DR^*)\\
&F_{ESO}(\pi_s^{e^*}, \pi_b^{e^*}, P_{CHP}^*, P_{MT}^*, DR^*) \ge F_{ESO}(\pi_s^{e^*}, \pi_b^{e^*}, P_{CHP}^*, P_{MT}^*, DR)
\end{aligned} \quad \text{(A3)}$$

Where the superscript * indicates the optimal equilibrium solution.

In the game process, when no interested subject can unilaterally change the strategy of the equilibrium solution to obtain benefits, it means that the game reaches the Stackelberg equilibrium and satisfies the conditions of equation (A3), then it is the equilibrium of the Stackelberg game.

B. *The Solving Process of Leader-Follower game*

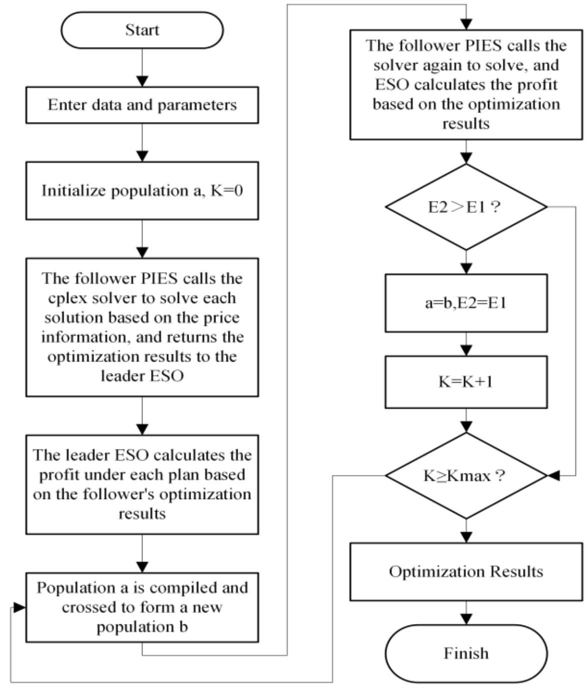

Figure B1. Flow chart of Stackelberg game solution

C. *Basic Data*

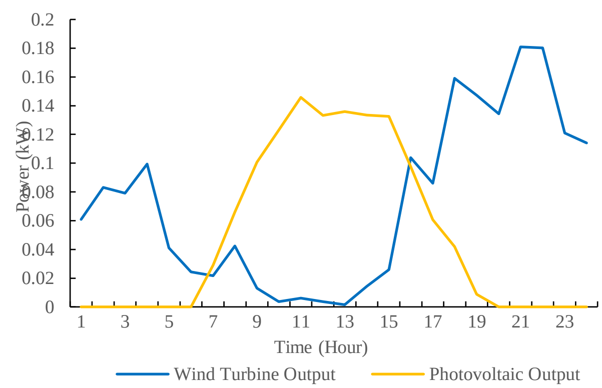

Figure C1. Wind and solar output prediction

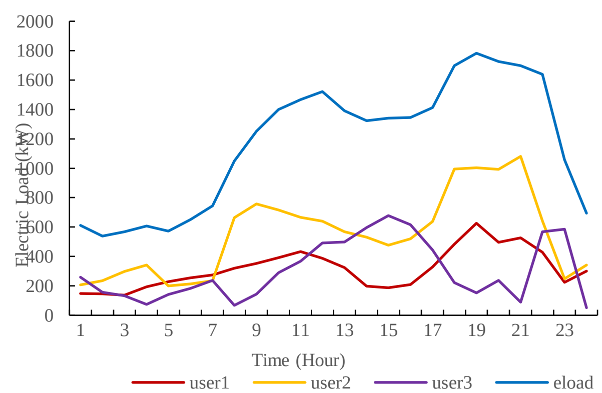

Figure C2. Daily load curves of users

TABLE II. PARAMETERS OF RENEWABLE CHP SYSTEM

Parameters of CHP system	
Boiler Capacity (kW)	300
Gas turbine capacity (kW)	800
Generator Electrical Efficiency	0.2
Preheat Recovery Efficiency	0.4

TABLE III. ELECTRICITY PRICE AND GAS PRICE

Data (CNY/kWh)		
Time (Hour)	Grid Price	Gas Price
23:00-06:00	0.25	3.075
06:00-13:00	0.8	2.355
13:00-19:00	0.53	3.075
19:00-23:00	0.8	2.355

REFERENCES

[1] H. Feng, "Domestic and foreign integrated energy supply industry development situation and commercial model study," *China Electrical Equipment Industry*, 2017(06):34-42.

[2] X. Zhou, S. Chen, Z. Yi, Y. Huang, S. Ma and Y. Zhao, "Technology features of the new generation power system in China," *Proceedings of the CSEE*, 2018, 38(07).

[3] S. Perdan and A. Azapagic, "Carbon trading: current schemes and future developments," *Energy tax*, 2011, 39 (10): 6040-6054.

[4] H. Jia, D. Wang, X. Xu and X. Yu, "Research on some key problems related to integrated energy systems," *Automation of Electric Power Systems*, 2015,39 (07): 198-207.

[5] C. Wang, C. Lv and P. Li, "Modeling and optimal operation of community integrated energy systems: a case study from China," *Applied Energy*, 2018, 230: 1242-1254.

[6] J. Cui, "Optimal operation method of integrated energy systems based on cooperative game," *North China Electric Power University (Beijing)*, 2019. DOI: 10.27140/dcnki.ghbbu.2019.001328.

[7] Q. Huan, L. Chen and M. Yu, "Explanation of current power system, typical usage and some prospects," *Proceedings of the CSEE*, 2014, 34(29):5009-5017.

[8] J. Li, Y. Zheng, B. Liu, X. Zhou and B. Pi, "Optimal operation of an integrated energy system with carbon capture system and combined heating and power based on a master-slave game," *Electrical Measurement and Instrumentation*, 1-11.

[9] H. Ren, N. Wang and Q. Wu, "Collaborative optimal scheduling and cost allocation of multiload aggregator considering ladder-type carbon trading," *Electric Power Construction*, 2024,45 (02): 171-182.

[10] J. Wang, Y. Ren and Z. Guo, "Optimal scheduling of integrated energy system considering integrated demand response and reward and punishment ladder carbon trading," *Energy Storage Science and Technology*, 2022, 11 (07): 2177-2187.

[11] C. Zhou, X. Ma and X. Guo, "Leader-follower game based optimized operation method for interaction of integrated energy system in industrial park," *Automation of Electric Power Systems*, 2019, 43 (07): 74-80.

[12] H. Wu, Y. Liu, Q. Yang, L. Xu and L. Zhong. "Optimal RIES Operation Strategy Based on Distributionally Robust Game Considering Demand Response," *Electric Power Construction*, 2022, 43(4): 108-118.

[13] N. Liu , H Li, X. Yu and L. Ma, "Multiparty Energy Management for Grid-Connected Microgrids With Heat and Electricity-Coupled Demand Response," *IEEE Trans. Industrial Informatics*, 2018,14(5):1887-1897.

[14] S. Liu, L. Song, B. Dai and N. Victor, "Analysis On Optimal Dispatching of Integrated Energy System With Additional Carbon Tax," *Journal of Engineering Thermophysics*, 2022,43(07):1790-1800.

[15] R. Zeng, X. Zhang and Y. Deng, "An off-design model to optimize CCHP-GSHP system considering carbon tax," *Energy conversion and management*, 2019, 189: 105-117.

[16] D. Olsen, Y. Dvorkin and R. Fernάndez-Blanco, "Optimal carbon taxes for emissions targets in the electricity sector," *IEEE Trans. Power Syst.*, 2018, 33(6): 5892-5901.

[17] Y. Cheng, N. Zhang and B. Zhang , "Low-carbon operation of multiple energy systems based on energy-carbon integrated prices," *IEEE Trans. Smart Grid*, 2019, 11(2): 1307-1318.

[18] H.Zhang, R. Zhang and J. Zhou, "Low-carbon economic dispatch of integrated energy system in campus based on Stackelberg game and hybrid carbon tax," *Acta Energiae Solaris Sinica*, 2023,44(09):9-17.

[19] Y. Zhang, R. Li, J. Zhao, Y. Wang and S. Wang, "Multi agent game collaborative optimization of integrated energy system considering carbon quota and integrated demand response," *Renewable Energy Resources*, 2024,42(03):388-397.

[20] R. Wang, S. Cheng, Y. Wang, J. Dai and X. Zuo, "Low-carbon and economic optimization of a regional integrated energy system based on a master-slave game with multiple stakeholders," *Power System Protection and Control*, 2022,50(05):12-21.

[21] P. Li,D. Wu andY. Li, "Optimal dispatching strategy of multi microgrid integrated energy system based on integrated demand response and master-slave game," *Proceedings of the CSEE*, 2021,41(04):1307-1321+1538.

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