Cooperative Optimal Scheduling of Integrated Energy System with P2G and Seasonal Hydrogen Storage

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***Abstract*—Hydrogen Integrated Energy Systems (HIES) represent a promising approach to enhance renewable energy utilization and mitigate CO_2 emissions, offering significant potential for sustainable development. Reasonable scheduling strategy is the key to the efficient operation of HIES. However, the system contains various types of energy conversion and energy storage equipment, such as P2G, long-term and short-term hydrogen storage, etc., which makes the optimal scheduling of the system extremely complicated and difficult to solve. The traditional optimal scheduling method based on a single time scale is difficult to achieve high performance of the system. Therefore, this paper proposes a two-layer cooperative optimal scheduling method for HIES based on multi-time scales. Firstly, according to the multi-time scale properties of the equipment performance analysis system, a multi-time scale sequence of the scheduling scheme is established, and a two-layer collaborative optimal scheduling model is further constructed. The upper layer optimizes the long-term charge and discharge plan of the seasonal energy storage equipment based on a long time scale sequence, and the lower layer optimizes the day-ahead optimization scheduling based on a short time scale sequence. Constraint conditions are constructed by long-term charge and discharge instructions to determine the scheduling plan of each equipment. Finally, evolutionary algorithm and CPLEX are used to solve the two-layer model. The effectiveness of the proposed method is verified by case analysis.**

Keywords—Hydrogen energy, integrated energy system, P2G

I. Introduction

The comprehensive energy system through multi-energy complementarity and energy cascade utilization, overall planning and coordination of renewable energy and traditional energy in the region, to meet the user's electricity, gas, heat, cold multiple load demands, to maximize the development of renewable energy consumption and improve energy efficiency, has become an important direction for the development of a new generation of energy technology. However, most renewable energy sources, including wind and solar, are volatile and intermittent [1, 2]. The amount of electricity generated by the wind and the wind fluctuates due to day and night, seasonal changes and weather conditions. When IES is connected to large-scale renewable energy sources, the spatio-temporal mismatch between renewable energy generation and multiple loads is particularly obvious, which makes the task of full absorption of renewable energy and efficient source-load matching more difficult.

In this context, power-to-gas (P2G) technology provides a new way to improve the utilization level of renewable energy [3]. P2G is a key technology to realize the bidirectional coupling and complementarity of electric energy and natural gas in IES. It can convert excess wind power/photovoltaic power generation into natural gas, thus promoting the cascade utilization of IES energy, improving the capacity of peak cutting and valley filling, and reducing energy waste [4]. On the other hand, seasonal energy storage technology can realize cross-season complementation of energy through long-term energy transfer, thus promoting the consumption of renewable energy [5]. At present, seasonal energy storage technologies mainly include seasonal heat storage [6] and seasonal hydrogen storage [7]. Hydrogen energy is an important clean energy, which is characterized by high efficiency, purity and multiple forms of energy conversion and utilization [8]. It is worth noting that hydrogen energy is a product of the P2G working process. Therefore, the simultaneous introduction of P2G and seasonal hydrogen storage into IES has gradually become a research focus [9,10]. Among them, how to formulate reasonable scheduling strategy is the key to efficient operation of hydrogen-based integrated energy system (HIES).

Wu et al. [11] proposed an operation optimization method for a HIES by considering power-to-gas and carbon-capture-storage technologies, then significantly reducing operation cost and CO_2 emission compared with the benchmark. Wu et al. [12] constructed a non-linear mixed integer dynamic scheduling optimization model for an integrated energy system with hydrogen storage, which was solved by the non-dominated sorting genetic algorithm. Wang et al. [13] considered uncertain characteristics of renewable energy and load, and proposed a stochastic optimal dispatching method based on improved

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spectral clustering for electricity-hydrogen-gas-heat integrated energy systems. Zhen et al. [14] proposed a dispatching optimization method of HIES for urban communities with considering carbon trading mechanism and uncertainty of renewable energy output.

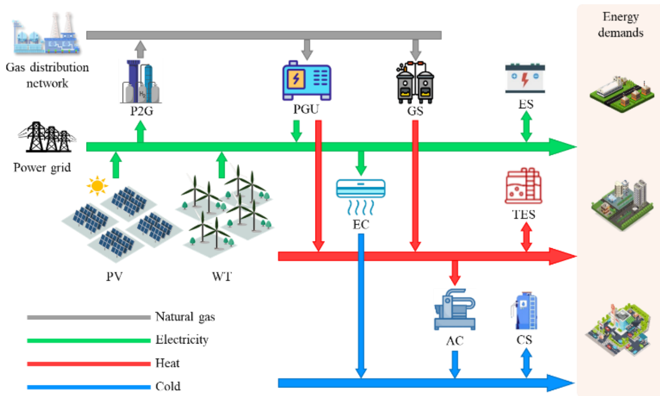


Fig. 1. Structure of the HIES.

Due to the introduction of technologies such as P2G and seasonal energy storage, the multi-energy complementary characteristics of IES have changed from a single time scale to a multi-time scale, which can cope with the mismatch between renewable energy and multi-load in day, day and cross-season. However, most of the existing studies on the optimization of HIES scheduling are based on a single time scale, and few consider the impact of seasonal changes of source loads on the optimization of HIES scheduling, which is difficult to give full play to the advantages of seasonal energy storage. Therefore, the multi-time scale attribute characteristics of the equipment are fully considered in this study, and a multi-time scale-based dual-layer cooperative optimal scheduling method is proposed. The main contributions are as follows:

- The two-layer cooperative optimal scheduling model is constructed, and the upper layer considers the seasonal changes of source and charge to optimize the charging and discharging plan of seasonal energy storage, so as to realize the seasonal complementarity of renewable energy. The lower layer optimizes the day ahead scheduling plan of energy conversion and energy storage equipment to meet the real-time balance of supply and demand of multi-energy flow.
- Three comparative cases were set up to verify the advantages of the proposed method in cost reduction.

II. System Description

The structure of HIES with high permeability of renewable energy is shown in Fig. 1. The system connects large-scale photovoltaic and wind power generation and supplies energy to a wide range of energy-using areas. HIES integrates multiple types of energy conversion and storage equipment to facilitate renewable energy consumption, including a P2G unit equipped with seasonal hydrogen storage equipment to cope with seasonal source-charge mismatch. The system is connected to the external power grid and the natural gas network to ensure stable and reliable energy supply.

The traditional day-ahead scheduling strategy based on a single time scale can only meet the supply and demand balance through equipment scheduling in a time period, which ignores the problem of source load mismatch in a longer time period. In order to achieve the best-performing source-charge matching, it is necessary to establish different time series to describe the operation characteristics of different types of equipment, and then schedule the equipment in the system on multiple time scales. Especially for energy storage equipment, short-term energy storage is usually daily, while long-term energy storage is seasonal or even a whole year, and there is coupling information between different time series. This means that the state of energy charge and discharge on a long time scale will affect the energy scheduling plan on a short time scale.

First, it is necessary to determine the time resolution and period of the Long timescale (LT) and Short timescale (ST), and the time series of the two time scales are represented by l and s respectively. LT scheduling is used to consider the long-term characteristics of renewable energy and load, and realize long-term energy transfer through equipment such as P2G and seasonal energy storage. The cycle of LT is the cycle of HIES optimal scheduling. ST scheduling realizes peak cutting and valley filling in a relatively short period through energy conversion and short-term energy storage equipment. There is a strong coupling relationship between the two time scales, that is, the time interval (Δt) of LT is the time period (T) of ST, which ensures the intercommunication of the time coupling information. In order to give full play to the seasonal complementary advantages of seasonal energy storage, the period and time interval of the long time scale are set as year and season, and the time interval of the short time scale is set as hour. The real-time energy balance of electricity, gas, heat and cold of the system is shown as follows:

$$\begin{cases} E_{\text{load}}^{t_s} = E_{\text{PV}}^{t_s} + E_{\text{WT}}^{t_s} + E_{\text{PGU}}^{t_s} + E_{\text{grid}}^{t_s} + E_{\text{ES},-}^{t_s} - E_{\text{ES},+}^{t_s} - E_{\text{P2G}}^{t_s} - E_{\text{EC}}^{t_s} \\ G_{\text{P2G}}^{t_s} + G_{\text{GDN}}^{t_s} = G_{\text{PGU}}^{t_s} + G_{\text{GB}}^{t_s} \\ H_{\text{load}}^{t_s} = H_{\text{PGU}}^{t_s} + H_{\text{GB}}^{t_s} + H_{\text{TES},-}^{t_s} - H_{\text{TES},+}^{t_s} - H_{\text{AC}}^{t_s} \\ C_{\text{load}}^{t_s} = C_{\text{AC}}^{t_s} + C_{\text{EC}}^{t_s} + C_{\text{CS},-}^{t_s} - C_{\text{CS},+}^{t_s} \end{cases}$$

where E, G, H, and C represent electricity, gas, heat, and cold energy respectively. The superscript is a time series and the subscript represents a renewable energy, energy conversion or energy storage equipment or load. In addition, the subscripts + and - indicate the charging or discharging state of the energy storage equipment, respectively.

Furthermore, refined models of energy conversion and energy storage equipment in the system are established based on different time scales. The P2G equipment is equipped with traditional short-term Hydrogen storage (HS) and long-term hydrogen storage (SHS) equipment to realize the flexible adjustment of electron-gas complementation on short and long time scales. The hydrogen produced by the electrolyzer has three streams: real-time methanation, short-term storage and seasonal storage. Therefore, the P2G model is:

$$Q_{\text{El}}^{t_s} = \eta_{\text{El}} E_{\text{P2G}}^{t_s} \tag{2}$$

$$0 \le Q_{\text{El}}^{t_s} \le N_{\text{P2G}}, \forall t_s \tag{3}$$

$$G_{\mathrm{P2G}}^{t_s} = \eta_{\mathrm{Me}} Q_{\mathrm{Me}}^{t_s} \tag{4}$$

$$0 \le G_{\mathrm{P2G}}^{t_s} \le N_{\mathrm{P2G}},\ \forall t_s \tag{5}$$

$$0 \le G_{\mathrm{P2G}}^{t_s} \le N_{\mathrm{P2G}},\ \forall t_s \tag{6}$$

where Q stands for hydrogen; The subscripts El and Me indicate electrolytic cells and methanation; η_{El} is the energy conversion efficiency of the electrolytic cell, η_{Me} is the methanation efficiency; $Q_{\mathrm{HS},+}^{t_s}$ and $Q_{\mathrm{SHS},+}^{t_s}$ the hydrogen filling amount for short-term and seasonal hydrogen storage respectively; $Q_{\mathrm{HS},-}^{t_s}$ and $Q_{\mathrm{SHS},-}^{t_s}$ are the hydrogen discharge amounts for short-term and seasonal hydrogen storage, respectively.

Short-term hydrogen storage equipment operates on a short time scale, and its hydrogen charging/discharging model is as follows:

$$0 \le Q_{\mathrm{HS},+}^{t_s} \le \varepsilon_{\mathrm{HS},+}^{t_s} \beta_{\mathrm{HS}} N_{\mathrm{HS}}, 0 \le Q_{\mathrm{HS},-}^{t_s} \le \varepsilon_{\mathrm{HS},-}^{t_s} \beta_{\mathrm{HS}} N_{\mathrm{HS}}, \forall t_s \tag{7}$$

$$S_{\mathrm{HS}}^{t_s+1} = \left(1-\gamma_{\mathrm{HS}}\right)^{\Delta t_s} S_{\mathrm{HS}}^{t_s} + \left(Q_{\mathrm{HS},+}^{t_s}\eta_{\mathrm{HS},+} - Q_{\mathrm{HS},-}^{t_s} / \eta_{\mathrm{HS},-}\right)\Delta t_s \tag{8}$$

$$0 \le S_{\mathrm{HS}}^{t_s} \le N_{\mathrm{HS}},\ \forall t_s \tag{9}$$

$$\begin{cases} 0 \le \varepsilon_{\mathrm{HS},+}^{t_s} + \varepsilon_{\mathrm{HS},-}^{t_s} \le 1,\ \forall t_s \\ \varepsilon_{\mathrm{HS},+}^{t_s}, \varepsilon_{\mathrm{HS},-}^{t_s} \in \{0,1\},\ \forall t_s \end{cases} \tag{10}$$

$$S_{\mathrm{HS}}^{0} = S_{\mathrm{HS}}^{T_s} = 0 \tag{11}$$

where $\varepsilon_{\mathrm{HS},+}^{t_s}$ and $\varepsilon_{\mathrm{HS},-}^{t_s}$ are the charging/discharging states of the short-term hydrogen storage equipment at time point t_s. $\eta_{\mathrm{HS},+}$ and $\eta_{\mathrm{HS},-}$ are the charging/discharging efficiency of short-term hydrogen storage.

The role of long-term hydrogen storage equipment is to transfer the energy generated by renewable energy sources between selected longer time intervals. Therefore, the model of the energy storage equipment is:

$$0 \le Q_{\mathrm{SHS},+}^{t_l,t_s} \le \varepsilon_{\mathrm{SHS},+}^{t_l} \beta_{\mathrm{SHS}} N_{\mathrm{SHS}}, \forall t_l, \forall t_s \tag{12}$$

$$0 \le Q_{\mathrm{SHS},-}^{t_l,t_s} \le \varepsilon_{\mathrm{SHS},-}^{t_l} \beta_{\mathrm{SHS}} N_{\mathrm{SHS}}, \forall t_l, \forall t_s \tag{13}$$

$$S_{\mathrm{SHS}}^{0} = S_{\mathrm{SHS}}^{T_l} = 0 \tag{14}$$

$$\begin{aligned} S_{\mathrm{SHS}}^{t_l,t_s+1} &= \left(1-\gamma_{\mathrm{SHS}}\right)^{\Delta t_s} S_{\mathrm{SHS}}^{t_l,t_s} + \\ &\left(Q_{\mathrm{SHS},+}^{t_l,t_s}\eta_{\mathrm{SHS},+} - Q_{\mathrm{SHS},-}^{t_l,t_s} / \eta_{\mathrm{SHS},-}\right)\Delta t_s \end{aligned} \tag{15}$$

$$\begin{aligned} S_{\mathrm{SHS}}^{t_l+1,0} &= S_{\mathrm{CS}}^{t_l,T_s} = \left(1-\gamma_{\mathrm{SHS}}\right)^{\Delta t_l} S_{\mathrm{SHS}}^{t_l,0} + \\ &\sum_{t_s=1}^{T_s} \left(1-\gamma_{\mathrm{SHS}}\right)^{T_s-t_s} \left(Q_{\mathrm{SHS},+}^{t_l,t_s}\eta_{\mathrm{SHS},+} - Q_{\mathrm{SHS},-}^{t_l,t_s} / \eta_{\mathrm{SHS},-}\right)\Delta t_s \end{aligned} \tag{16}$$

$$0 \le S_{\mathrm{SHS}}^{t_l} \le N_{\mathrm{SHS}},\ \forall t_l \tag{17}$$

$$\begin{cases} 0 \le \varepsilon_{\mathrm{SHS},+}^{t_l} + \varepsilon_{\mathrm{SHS},-}^{t_l} \le 1,\ \forall t_l \\ \varepsilon_{\mathrm{SHS},+}^{t_l}, \varepsilon_{\mathrm{SHS},-}^{t_l} \in \{0,1\},\ \forall t_l \end{cases} \tag{18}$$

where $\varepsilon_{\mathrm{SHS},+}^{t_l}$ and $\varepsilon_{\mathrm{SHS},-}^{t_l}$ are the charging/discharging states of the seasonal hydrogen storage equipment at time point t_l. $\eta_{\mathrm{SHS},+}$ and $\eta_{\mathrm{SHS},-}$ are the charging/discharging efficiency of seasonal hydrogen storage equipment. Among them, (14)-(16) define the working mechanism of seasonal hydrogen storage equipment on two time scales, while (18) restricts the energy storage equipment to maintain the same charging/discharging working state at any time within the time point.

The generator set model is:

$$E_{\mathrm{PGU}}^{t_s} = G_{\mathrm{PGU}}^{t_s} \eta_{\mathrm{PGU}}^{t_s} \tag{19}$$

$$0 \le E_{\mathrm{PGU}}^{t_s} \le N_{\mathrm{PGU}},\ \forall t_s \tag{20}$$

$$H_{\mathrm{PGU}}^{t_s} = G_{\mathrm{PGU}}^{t_s} \left(1-\eta_{\mathrm{PGU}}^{t_s}\right) \eta_{\mathrm{rh}} \tag{21}$$

The absorption refrigerator model is:

$$C_{\mathrm{AC}}^{t_s} = H_{\mathrm{AC}}^{t_s} COP_{\mathrm{AC}} \tag{22}$$

$$0 \le C_{\mathrm{AC}}^{t_s} \le N_{\mathrm{AC}},\ \forall t_s \tag{23}$$

The electric refrigerator model is:

$$C_{\mathrm{EC}}^{t_s} = E_{\mathrm{EC}}^{t_s} COP_{\mathrm{EC}} \tag{24}$$

$$0 \le C_{\mathrm{EC}}^{t_s} \le N_{\mathrm{EC}},\ \forall t_s \tag{25}$$

The gas-fired boiler model is:

$$H_{\mathrm{GB}}^{t_s} = G_{\mathrm{GB}}^{t_s} \eta_{\mathrm{GB}} \tag{26}$$

$$0 \le H_{\mathrm{GB}}^{t_s} \le N_{\mathrm{GB}},\ \forall t_s \tag{27}$$

Heat storage, cold storage and electricity storage equipment improve the operational flexibility of the system on a short time scale by adjusting the IES thermoelectric output ratio, which is modeled as:

$$0 \le H_{\mathrm{TES},+}^{t_s} \le \varepsilon_{\mathrm{TES},+}^{t_s} \beta_{\mathrm{TES}} N_{\mathrm{TES}}, \forall t_s \tag{28}$$

$$0 \le H_{\mathrm{TES},-}^{t_s} \le \varepsilon_{\mathrm{TES},-}^{t_s} \beta_{\mathrm{TES}} N_{\mathrm{TES}}, \forall t_s \tag{29}$$

$$\begin{aligned} S_{\mathrm{TES}}^{t_s+1} &= \left(1-\gamma_{\mathrm{TES}}\right)^{\Delta t_s} S_{\mathrm{TES}}^{t_s} \\ &+\left(H_{\mathrm{TES},+}^{t_s}\eta_{\mathrm{TES},+} - H_{\mathrm{TES},-}^{t_s} / \eta_{\mathrm{TES},-}\right)\Delta t_s \end{aligned} \tag{30}$$

$$0 \le S_{\mathrm{TES}}^{t_s} \le N_{\mathrm{TES}},\ \forall t_s \tag{31}$$

$$\begin{cases} 0 \le \varepsilon_{\mathrm{TES},+}^{t_s} + \varepsilon_{\mathrm{TES},-}^{t_s} \le 1,\ \forall t_s \\ \varepsilon_{\mathrm{TES},+}^{t_s}, \varepsilon_{\mathrm{TES},-}^{t_s} \in \{0,1\},\ \forall t_s \end{cases} \tag{32}$$

$$S_{\mathrm{TES}}^{0} = S_{\mathrm{TES}}^{T_s} = 0 \tag{33}$$

where $\varepsilon_{\mathrm{TES},+}^{t_s}$ and $\varepsilon_{\mathrm{TES},-}^{t_s}$ are the charging/releasing state of the heat storage water tank at time point t_s; $\eta_{\mathrm{TES},+}$ and $\eta_{\mathrm{TES},-}$ are the charging/releasing efficiency of the heat storage tank. The model of the cold storage equipment and the battery is similar to the model of the hot water storage tank.

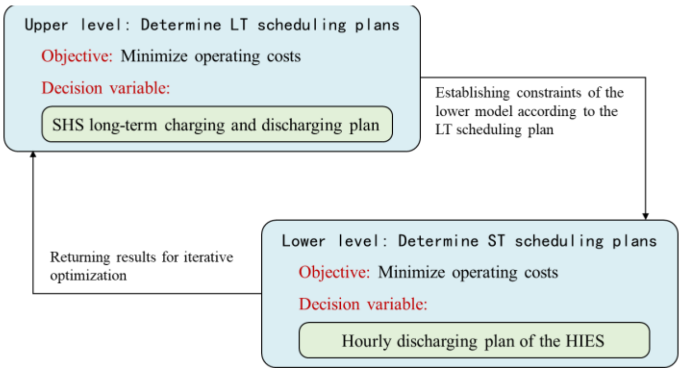


Fig. 2. Schematic of the bi-level coordinated optimization framework.

III. Two-Layer Cooperative Optimal Scheduling

In order to realize the economical and efficient operation of the system, based on the characteristics of multiple time scales of the system, a dual-layer cooperative optimal scheduling model is constructed, and its technical route is shown in Fig. 2. The upper layer is long-term optimization scheduling, aiming at the lowest total operating cost in a long time scale cycle, and formulating long-term charging and discharging plans for seasonal energy storage equipment; The lower layer is short time scale optimization scheduling. Based on the upper optimization results, the energy conversion and short-term energy storage equipment scheduling plan are optimized by considering the supply and demand balance constraints of multi-energy flow. The nested optimization idea is used to establish the interaction mechanism between different scheduling layers. The results of the upper layer are used to construct the constraints of the lower layer optimization, and the optimization results of the lower layer are returned to the upper layer to calculate the optimization target value of the upper layer, and the double-layer iterative optimization is performed until the optimal solution is obtained.

A. Upper Level Long Time Scale Optimization Scheduling

In order to realize the economical and efficient operation of the system, the long-scale optimization scheduling model of the upper layer aims at the lowest operating cost, which consists of the interaction cost with the power grid, the gas purchase cost and the carbon emission penalty cost. Therefore, the objective function is defined as:

$$\min \ COST_{\mathrm{oc}} = \sum_{t_l=1}^{T_l} \left(COST_{\mathrm{grid}}^{t_l} + COST_{\mathrm{GDN}}^{t_l} + COST_{\mathrm{CE}}^{t_l} \right) \tag{34}$$

Where, $P_{\mathrm{grid},+}(t)$ and $P_{\mathrm{grid},-}(t)$ are the selling power, buying price and selling price of the grid at time t respectively; P_{ng} is the gas price. The upper level model aims to develop the optimal long-term charging and discharging plan for seasonal energy storage equipment, and the optimization variables are $\varepsilon_{\mathrm{SHS},+}^{t_l}$ and $\varepsilon_{\mathrm{SHS},-}^{t_l}$, which must meet the constraint (18).

B. Lower Level Short Time Scale Optimization Scheduling

The lower level model is based on the constraints of the charging and discharging plan of the upper level seasonal energy storage equipment to optimize the scheduling plan of each equipment on a short time scale. The optimization goal of the lower layer is the same as that of the upper layer, in order to minimize the operating cost during the scheduling cycle. Since the period T_s of optimization scheduling in the lower layer is consistent with t_l, the lower layer contains T_l optimization subproblems, and the objective function of each subproblem is expressed as:

$$\begin{aligned} \min \ COST_{\mathrm{oc}}^{t_l} &= COST_{\mathrm{grid}}^{t_l} + COST_{\mathrm{GDN}}^{t_l} + COST_{\mathrm{CE}}^{t_l} \\ &= \sum_{t_s=1}^{T_s} \left(P_{\mathrm{grid}}^{t_l,t_s} E_{\mathrm{grid}}^{t_l,t_s} + P_{\mathrm{ng}} G_{\mathrm{GDN}}^{t_l,t_s} + P_{\mathrm{CT}} CE^{t_l,t_s} \right) \end{aligned} \tag{35}$$

where $P_{\mathrm{grid},+}(t)$ and $P_{\mathrm{grid},-}(t)$ are the selling power, buying price and selling price of the grid at time t respectively; P_{ng} is the gas price.

The lower level model aims to develop the optimal real-time energy conversion and storage equipment scheduling plan to meet the multi-load demand. The optimization variables include the real-time output plan of each energy conversion equipment and the real-time charging and discharging plan of each energy storage equipment, which must meet the constraints of supply and demand balance of multi-energy flow and equipment operation constraints.

C. Solution Method

The upper optimization model is a 0-1 integer programming problem, while the lower optimization model is a mixed integer linear programming problem. Therefore, evolutionary algorithm and CPLEX solver are organically combined to solve the two-layer optimization model. The solution steps are as follows:

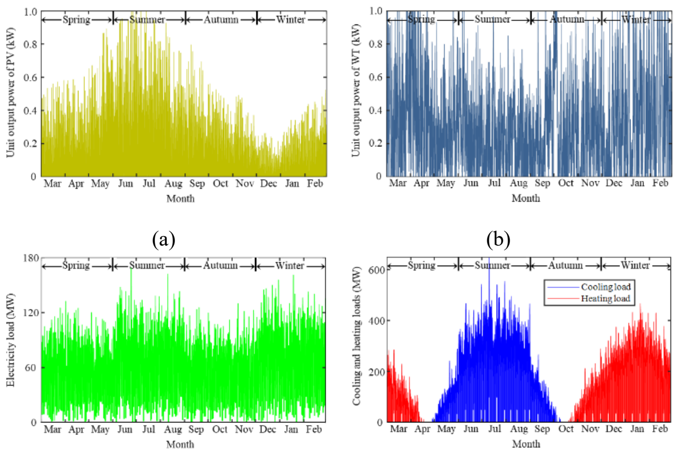
Step 1: Set algorithm parameters, enter HIES technical parameters, annual renewable energy power generation and user load data, energy price, etc;
Step 2: The evolutionary algorithm randomly generates the initial population, including p long-term charging and discharging plans of seasonal energy storage;
Step 3: New populations are generated through selection, crossover and recombination;
Step 4: The population information and the required data are passed to the lower layer, and the CPLEX solver is called to solve the optimal real-time scheduling scheme for each individual, and the minimum running cost is returned to the upper layer to calculate the fitness of each individual;
Step 5: If the convergence condition is met, the iteration is stopped and the optimal scheduling scheme of the system is output. If not, the next iteration is entered.

IV. Case Study

A. Parameter Setting

The annual source load data of an energy-using region in Shandong Province is selected for case study, as shown in Fig. 3. Taking into account the seasonal nature of renewable energy and load, the time series begins in March. It can be seen from the figure that there are mismatches in the source-charge distribution on multiple time scales over the whole year. Table I summarizes the relevant parameters of IES. Electricity prices are shown in Table II and natural gas ladder prices are shown in Table III.

In order to verify the effectiveness and advancement of the proposed optimal scheduling method, 3 kinds of scheduling scenarios are set for comparative analysis: (1) Adopt the cooperative optimal scheduling method proposed in this paper; (2) The traditional single time scale scheduling method; (3) IES optimization scheduling method without P2G configuration.



(d)

Fig. 3. Annual hourly source–load data. (a) Annual solar power output data per unit capacity; (b) Annual wind power output data per unit capacity; (c) Annual electrical load data; (d) Annual cooling and heat load data.

TABLE I. PARAMETERS RELATED TO EQUIPMENT

Equipment name	Capacity	Efficiency
Photovoltaic (MW)	220	-
Wind turbine (MW)	300	-
P2G (MW)	210	Hydrogen production: 0.75 Methanation: 0.85
Power generation unit (MW)	70	Power generation: 0.35 Heating: 0.55
Absorption refrigerator (MW)	100	0.9
Electric refrigerator (MW)	420	3
Gas-fired boiler (MW)	280	0.9
Short-term hydrogen storage tank (MWh)	180	0.95
Seasonal hydrogen storage tank (MWh)	45000	0.99
Battery (MWh)	70	0.95
Cold water storage tank (MWh)	650	0.95
Heat water storage tank (MWh)	460	0.95

TABLE II. TIME-OF-USE ELECTRICITY PRICES

Type	10:00–13:00; 18:00–23:00	7:00–10:00; 13:00–18:00	23:00 – 7:00
Buy electricity (yuan /kWh)	1.134	0.826	0.564
Selling electricity (Yuan /kWh)	0.4	0.3	0.2

TABLE III. TIERED GAS PRICES

Natural gas consumption ($\times 10^5$ MWh/quarter)	0-1	1-1.6	1.6-8
Natural gas price (yuan /kWh)	0.376	0.4512	0.564

B. Results and Discussion

Fig. 4 summarizes the operation cost results of the three simulation scenarios. Among them, the multi-time-scale cooperative optimal scheduling method proposed in this study gives the lowest annual operation cost, which is reduced by 11.39% compared with the traditional single-time-scale scheduling method. Moreover, it can be clearly seen that the operation cost can be greatly reduced after the P2G equipment is configured in the integrated energy system, because the P2G equipment can improve the system's renewable energy consumption capacity, thereby reducing the cost of electricity and gas purchase.

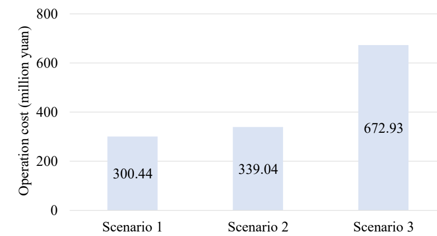


Fig. 4. Operation costs for three simulation scenarios.

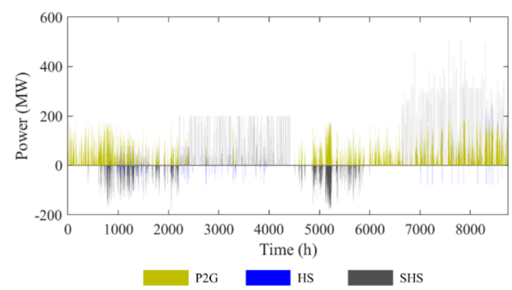


Fig. 5. Annual operation plan of hydrogen energy equipment for scenario 1.

The annual operating cost of IES is further subdivided into four seasons: spring, summer, autumn and winter, as shown in Table IV. The proposed multi-time scale collaborative optimization can effectively reduce the difference in operating cost between the four seasons. Compared with the traditional single-time scale scheduling method, the cost of spring and autumn has increased, but the cost of summer and winter has dropped more sharply, indicating that seasonal energy storage equipment has played an important role in realizing energy transfer between seasons. Thus, the source load matching is realized in a more economical way.

TABLE IV. TIME-OF-USE ELECTRICITY PRICES

Scenario	Spring	Summer	Autumn
1	18.08	60.63	32.84
2	17.82	77.72	30.84
3	81.03	191.81	85.93

Fig. 5 shows the annual operation plan of each hydrogen energy equipment in the system in scenario 1. By adding long time scale optimization, seasonal hydrogen storage equipment can be charged in one season and discharged in another season to promote seasonal renewable energy and load matching. As can be seen from the Fig. 5, in the spring and autumn, excess electricity generated by renewable energy sources is converted into hydrogen through electrolytic cells in the P2G unit. The hydrogen is then stored in seasonal hydrogen storage facilities and released in summer and winter to reduce the seasonal mismatch between source and load, which in turn minimizes the amount of natural gas purchased to reduce operating costs.

V. Conclusion

This research fully considers the multi-time scale characteristics of HIES with the introduction of P2G and seasonal energy storage technology, and then proposes a collaborative optimization scheduling method to reduce the operating cost of the system. The results show that the proposed method realizes the energy transfer between seasons, and can promote the efficient and economical matching of source and load. Compared with the traditional single-time-scale optimization method, the annual operating cost of the optimized HIES method is reduced by 11.39%. In addition, the introduction of P2G and seasonal energy storage technology enhances the electrical coupling complementarity of the system, which significantly improves the absorption capacity of renewable energy.

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