

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

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Abstract—Hydrogen-based integrated energy systems (HIESs) represent a promising approach to enhance renewable energy utilization and mitigate CO₂ emissions, offering significant potential for sustainable development. Reasonable scheduling strategy is the key to the efficient operation of HIESs. However, the system contains various types of energy conversion and energy storage equipment, such as power-to-gas (P2G), long-term and short-term hydrogen storage, etc., which makes the optimal scheduling extremely complicated and difficult to solve. Traditional optimal scheduling methods based on a single time scale are difficult to achieve high performance of the system. Therefore, this study proposes a two-layer cooperative optimal scheduling method for the HIES based on multiple timescales. Firstly, the multi-timescale attributes of the system are analyzed based on equipment performance, and a multi-timescale sequence is established for the scheduling scheme. Then, a two-layer cooperative 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 timescale sequence. The lower layer based on a short timescale sequence constructs constraints by long-term charge and discharge instructions to optimize the hourly scheduling scheme 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—integrated energy system, optimal scheduling, P2G, seasonal hydrogen storage

I. INTRODUCTION

The integrated energy system (IES) can satisfy the user's electricity, gas, heat and cold demands by multi-energy complementarity and energy cascade utilization, to maximize the development of renewable energy consumption and improve energy efficiency. It has become an important direction for the development of a new generation of energy technology. However, most renewable energy sources, such as wind and solar, are volatile and intermittent [1, 2]. The amount of electricity generated by the solar and 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, the 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 the IES. It can convert excess wind power/photovoltaic power generation into natural gas, thus promoting the energy cascade utilization of IES, 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 (SHS) [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 systems (HIESs).

Wu et al. [11] proposed an operation optimization method for a HIES by considering P2G and carbon-capture-storage technologies, then significantly reducing operation cost and CO₂ emission compared with the benchmark. Fang et al. [12] constructed a non-linear mixed integer dynamic scheduling optimization model for an IES 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 spectral clustering for electricity-hydrogen-gas-heat IESs. Zhen et al. [14] proposed a operation optimization method of a HIES for urban communities with considering carbon trading mechanism and uncertainty of renewable energy output.

Due to the introduction of technologies such as P2G and seasonal energy storage, the multi-energy complementary characteristics of IES have changed from single-timescale to multi-timescale, which can cope with the mismatch between renewable energy and multi-loads in inner-day, inter-day and cross-season. However, most of the existing studies on the optimal scheduling of HIESs are based on the single timescale, and few consider the impact of seasonal changes of source loads

on the optimal scheduling of HIESs, which is difficult to give full play to the advantages of seasonal energy storage. Therefore, the multi-timescale attribute characteristics of the equipment are fully considered in this study, and a multi-timescale two-layer cooperative optimal scheduling method is proposed. The main contributions are as follows:

- The two-layer cooperative optimal scheduling model is constructed. The upper layer considers the seasonal changes of renewable energy and loads 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 hourly scheduling plan of energy conversion and energy storage equipment to meet the real-time balances of supply and demand of multi-energy flows.
- Three comparative cases are set up to verify the advantages of the proposed method in cost reduction.

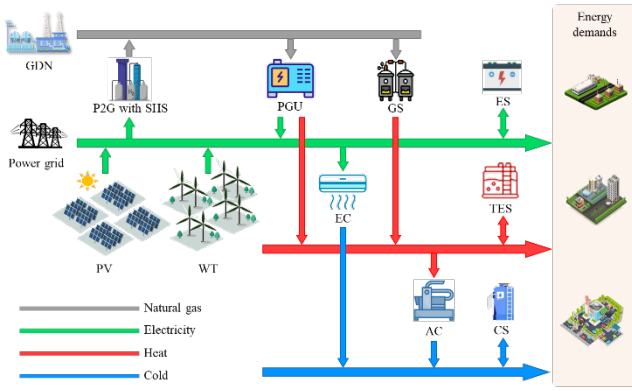


Fig. 1. Structure of the HIES.

II. SYSTEM DESCRIPTION

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

The traditional day-ahead scheduling strategy based on the single timescale can only meet the supply and demand balances 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-load 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 timescales. 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 timescale will affect the energy scheduling plan on a short timescale.

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 timescales 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 timescales, 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 LT are set as year and season, and the time interval of the short time scale is set as hour. The real-time energy balances of electricity, gas, heat and cold of the system is shown as follows:

$$\begin{cases} E_{load}^t = E_{PV}^t + E_{WT}^t + E_{PGU}^t + E_{grid}^t + E_{ES,-}^t - E_{ES,+}^t - E_{P2G}^t - E_{EC}^t \\ G_{P2G}^t + G_{GDN}^t = G_{PGU}^t + G_{GB}^t \\ H_{load}^t = H_{PGU}^t + H_{GB}^t + H_{TES,-}^t - H_{TES,+}^t - H_{AC}^t \\ C_{load}^t = C_{AC}^t + C_{EC}^t + C_{CS,-}^t - C_{CS,+}^t \end{cases} \quad (1)$$

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 SHS to realize the flexible adjustment of electricity-gas complementation on short and long timescales. The hydrogen produced by the electrolyzer has three streams: real-time methanation, short-term storage and seasonal storage. Therefore, the P2G model is:

$$Q_{El}^t = \eta_{El} E_{P2G}^t \quad (2)$$

$$0 \leq Q_{El}^t \leq N_{P2G}, \forall t_s \quad (3)$$

$$G_{P2G}^t = \eta_{Me} Q_{Me}^t \quad (4)$$

$$0 \leq G_{P2G}^t \leq N_{P2G}, \forall t_s \quad (5)$$

$$Q_{Me}^t = Q_{El}^t - Q_{SHS,+}^t + Q_{SHS,-}^t - Q_{HS,+}^t + Q_{HS,-}^t \quad (6)$$

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; $Q_{HS,+}^t$ and $Q_{SHS,+}^t$ the hydrogen filling amount for HS and SHS respectively; $Q_{HS,-}^t$ and $Q_{SHS,-}^t$ are the hydrogen discharge amounts for HS and SHS, respectively.

The HS operates on the short timescale, and its hydrogen charging/discharging model is as follows:

$$0 \leq Q_{HS,+}^{t_s} \leq \varepsilon_{HS,+}^{t_s} \beta_{HS} N_{HS}, 0 \leq Q_{HS,-}^{t_s} \leq \varepsilon_{HS,-}^{t_s} \beta_{HS} N_{HS}, \forall t_s \quad (7)$$

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

$$0 \leq S_{HS}^{t_s} \leq N_{HS}, \forall t_s \quad (9)$$

$$\begin{cases} 0 \leq \varepsilon_{HS,+}^{t_s} + \varepsilon_{HS,-}^{t_s} \leq 1, \forall t_s \\ \varepsilon_{HS,+}^{t_s}, \varepsilon_{HS,-}^{t_s} \in \{0, 1\}, \forall t_s \end{cases} \quad (10)$$

$$S_{HS}^0 = S_{HS}^{T_s} = 0 \quad (11)$$

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

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

$$0 \leq Q_{SHS,+}^{t_l,t_s} \leq \varepsilon_{SHS,+}^{t_l,t_s} \beta_{SHS} N_{SHS}, \forall t_l, \forall t_s \quad (12)$$

$$0 \leq Q_{SHS,-}^{t_l,t_s} \leq \varepsilon_{SHS,-}^{t_l,t_s} \beta_{SHS} N_{SHS}, \forall t_l, \forall t_s \quad (13)$$

$$S_{SHS}^0 = S_{SHS}^{T_l} = 0 \quad (14)$$

$$S_{SHS}^{t_l,t_s+1} = (1 - \gamma_{SHS})^{\Delta t_s} S_{SHS}^{t_l,t_s} + (Q_{SHS,+}^{t_l,t_s} \eta_{SHS,+} - Q_{SHS,-}^{t_l,t_s} / \eta_{SHS,-}) \Delta t_s \quad (15)$$

$$S_{SHS}^{t_l+1,0} = S_{SHS}^{t_l,T_s} = (1 - \gamma_{SHS})^{\Delta t_s} S_{SHS}^{t_l,0} + \sum_{t_s=1}^{T_s} (1 - \gamma_{SHS})^{T_s-t_s} (Q_{SHS,+}^{t_l,t_s} \eta_{SHS,+} - Q_{SHS,-}^{t_l,t_s} / \eta_{SHS,-}) \Delta t_s \quad (16)$$

$$0 \leq S_{SHS}^{t_l} \leq N_{SHS}, \forall t_l \quad (17)$$

$$\begin{cases} 0 \leq \varepsilon_{SHS,+}^{t_l} + \varepsilon_{SHS,-}^{t_l} \leq 1, \forall t_l \\ \varepsilon_{SHS,+}^{t_l}, \varepsilon_{SHS,-}^{t_l} \in \{0, 1\}, \forall t_l \end{cases} \quad (18)$$

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

The model of the power generation unit (PGU) is:

$$E_{PGU}^{t_s} = C_{PGU}^{t_s} \eta_{PGU}^{t_s} \quad (19)$$

$$0 \leq E_{PGU}^{t_s} \leq N_{PGU}, \forall t_s \quad (20)$$

$$H_{PGU}^{t_s} = G_{PGU}^{t_s} (1 - \eta_{PGU}^{t_s}) \eta_{rh} \quad (21)$$

The model of the absorption chiller (AC) is:

$$C_{AC}^{t_s} = H_{AC}^{t_s} COP_{AC} \quad (22)$$

$$0 \leq C_{AC}^{t_s} \leq N_{AC}, \forall t_s \quad (23)$$

The model of the electric chiller (EC) is:

$$C_{EC}^{t_s} = E_{EC}^{t_s} COP_{EC} \quad (24)$$

$$0 \leq C_{EC}^{t_s} \leq N_{EC}, \forall t_s \quad (25)$$

The model of the gas boiler (GB) is:

$$H_{GB}^{t_s} = G_{GB}^{t_s} \eta_{GB} \quad (26)$$

$$0 \leq H_{GB}^{t_s} \leq N_{GB}, \forall t_s \quad (27)$$

Thermal energy storage (TES), cold storage (CS) and electricity storage (ES) improve the operational flexibility of the system on the short timescale by adjusting the HIES thermoelectric output ratio. The TES is modeled as:

$$0 \leq H_{TES,+}^{t_s} \leq \varepsilon_{TES,+}^{t_s} \beta_{TES} N_{TES}, \forall t_s \quad (28)$$

$$0 \leq H_{TES,-}^{t_s} \leq \varepsilon_{TES,-}^{t_s} \beta_{TES} N_{TES}, \forall t_s \quad (29)$$

$$S_{TES}^{t_s+1} = (1 - \gamma_{TES})^{\Delta t_s} S_{TES}^{t_s} + (H_{TES,+}^{t_s} \eta_{TES,+} - H_{TES,-}^{t_s} / \eta_{TES,-}) \Delta t_s \quad (30)$$

$$0 \leq S_{TES}^{t_s} \leq N_{TES}, \forall t_s \quad (31)$$

$$\begin{cases} 0 \leq \varepsilon_{TES,+}^{t_s} + \varepsilon_{TES,-}^{t_s} \leq 1, \forall t_s \\ \varepsilon_{TES,+}^{t_s}, \varepsilon_{TES,-}^{t_s} \in \{0, 1\}, \forall t_s \end{cases} \quad (32)$$

$$S_{TES}^0 = S_{TES}^{T_s} = 0 \quad (33)$$

where $\varepsilon_{TES,+}^{t_s}$ and $\varepsilon_{TES,-}^{t_s}$ are the charging and discharging state of the THS at time point t_s , respectively; $\eta_{TES,+}$ and $\eta_{TES,-}$ are the charging and discharging efficiency of the TES, respectively. The models of the CS and the ES are similar to the model of the TES.

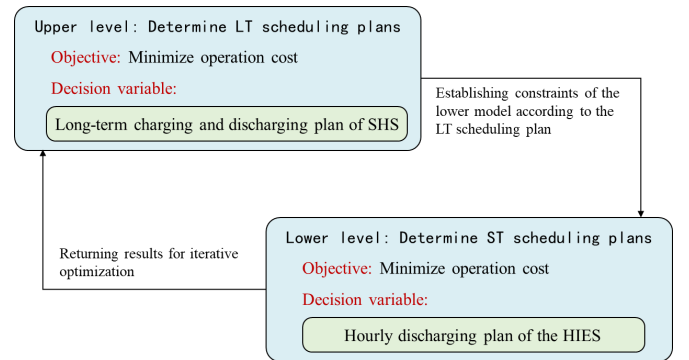


Fig. 2. Schematic of the two-layer cooperative optimization framework.

III. TWO-LAYER COOPERATIVE OPTIMAL SCHEDULING

In order to realize the economical and efficient operation of the HIES, a two-layer cooperative optimal scheduling model is constructed based on the multi-timescale characteristics. Its technical route is shown in Fig. 2. The upper layer is LT scheduling optimization, aiming at the lowest total operation

cost in the LT cycle, and formulating long-term charging and discharging plans for SHS. The lower layer is ST scheduling optimization. Based on the upper optimization results, the energy conversion and short-term energy storage equipment scheduling plans are optimized by considering the source-load balances constraints of multi-energy flows. 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 objective value of the upper layer, and the two-layer iterative optimization is performed until the optimal solution is obtained.

A. Upper Layer Scheduling Optimization

In order to realize the economical and efficient operation of the system, the LT scheduling model of the upper layer aims at the lowest operation 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:

$$\min \text{COST}_{\text{oc}} = \sum_{t_l=1}^{T_l} (\text{COST}_{\text{grid}}^{t_l} + \text{COST}_{\text{GDN}}^{t_l} + \text{COST}_{\text{CE}}^{t_l}) \quad (34)$$

The upper layer model aims to develop the optimal long-term charging and discharging plan for the SHS, and the optimization variables are $\varepsilon_{\text{SHS},+}^{t_l}$ and $\varepsilon_{\text{SHS},-}^{t_l}$, which needs to meet the constraint (18).

B. Lower Level Scheduling Optimization

The lower level model is based on the constraints of the charging and discharging plan of the SHS from the upper layer to optimize the scheduling plan of each equipment on the ST. The optimization objective of the lower layer is the same as that of the upper layer, to minimize the operation 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:

$$\begin{aligned} \min \text{COST}_{\text{oc}}^{t_l} &= \text{COST}_{\text{grid}}^{t_l} + \text{COST}_{\text{GDN}}^{t_l} + \text{COST}_{\text{CE}}^{t_l} \\ &= \sum_{t_s=1}^{T_s} (P_{\text{grid}}^{t_l,t_s} E_{\text{grid}}^{t_l,t_s} + P_{\text{ng}} G_{\text{GDN}}^{t_l,t_s} + P_{\text{CT}} CE^{t_l,t_s}) \end{aligned} \quad (35)$$

where P_{grid} is electricity price and P_{ng} is the gas price. P_{CT} and CE are the unit price of the carbon tax and the carbon emissions of the system, respectively.

The lower level model aims to develop the optimal hourly scheduling plan for energy conversion and storage equipment to meet the multiple loads. The optimization variables include the hourly output plan of each energy conversion equipment and the hourly charging and discharging plan of each energy storage equipment, which must meet the constraints of supply and demand balances of multi-energy flows 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 the SHS.

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 hourly scheduling scheme for each individual, and the minimum operation 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 HIES 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-load distribution on multiple timescales over the whole year. Table I summarizes the relevant parameters of the HIES. 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, three scheduling scenarios are set for comparative analysis: (1) The cooperative optimal scheduling method proposed in this study. (2) The traditional single-timescale optimal scheduling method. (3) The optimal scheduling method of the IES without P2G.

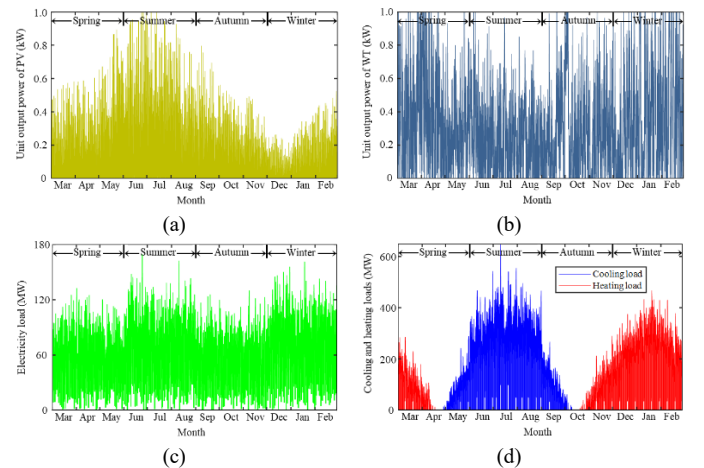


Fig. 3. Annual hourly source-load curves: (a) Annual PV output per unit capacity; (b) Annual WT output per unit capacity; (c) Annual electrical load; (d) Annual cooling and heating load.

TABLE I. PARAMETERS RELATED TO EQUIPMENT

Equipment	Capacity	Efficiency
PV	220 MW	-
WT	300 MW	-
P2G	210 MW	Hydrogen production: 0.75 Methanation: 0.85 Power generation: 0.35 Heating: 0.55
PGU	70 MW	0.9
AC	100 MW	3
GB	420 MW	0.9
HS	180 MWh	0.95
SHS	45000 MWh	0.99
ES	70 MWh	0.95
CS	650 MWh	0.95
TES	460 MWh	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-timescale 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-timescale scheduling method. Moreover, it can be clearly seen that the operation cost can be greatly reduced after the P2G equipment is configured in the IES, because the P2G equipment can improve the renewable energy consumption capacity for the system, thereby reducing the cost of electricity and gas purchase.

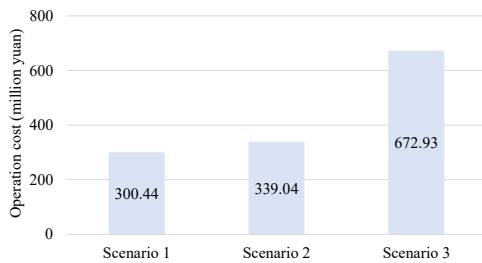


Fig. 4. Operation costs for three simulation scenarios.

The annual operation cost of the HIES is further subdivided into four seasons: spring, summer, autumn and winter, as shown in Table IV. The proposed multi-timescale cooperative optimization can effectively reduce the difference in operation cost between the four seasons. Compared with the traditional single-timescale scheduling method, the operation cost in the spring and autumn has increased, but the operation cost in the 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. SEASONAL OPERATION COSTS FOR THREE SIMULATION SCENARIOS (MILLION YUAN)

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

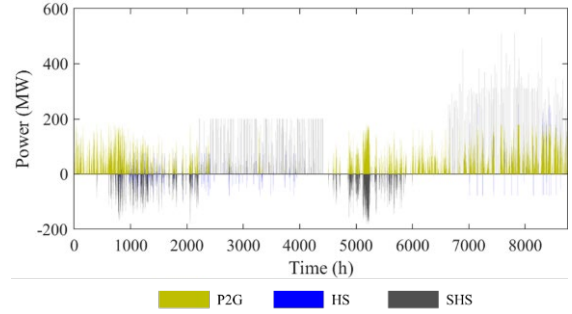


Fig. 5. Annual operation plan of hydrogen energy equipment for scenario 1.

Fig. 5 shows the annual operation plan of each hydrogen energy equipment in the HIES for scenario 1. By adding LT optimization, SHS 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 the SHS 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 operation cost.

V. CONCLUSION

This study fully considers the multi-timescale characteristics of the HIES with P2G and seasonal energy storage, and proposes a cooperative optimal scheduling method to minimize the operation cost of the system. Simulation 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-timescale optimization method, the annual operation cost of the HIES optimized by the proposed method is reduced by 11.39%. In addition, the introduction of P2G and seasonal energy storage technology enhances the electricity-gas complementarity coupling of the system, which significantly improves the consumption capacity of renewable energy.

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