Optimizing economic viability of large-scale power-to-H_2-to-power system based on hydrogen-blended gas turbines: A comprehensive analysis on electricity-carbon market coordination

Xiaorui Chen[a], Yanxin Li[a], Xiaoqu Han[a]*, Shenggeng Zhou[a], Qiangxu Gao[a] and Junjie Yan[a]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, China, hanxiaoqu@mail.xjtu.edu.cn, CA

Abstract:

The large-scale and accelerated deployment of renewable energy is pivotal to achieving carbon peaking and carbon neutrality targets. However, renewable energy stations are exposed to prominent revenue uncertainty and operational risks in electricity markets. The power-to-H_2-to-power system (PtH2tP) integrated with salt cavern hydrogen storage and high-proportion hydrogen-blended gas turbines (HBGTs) is a promising pathway for renewable energy accommodation, as a long-duration energy storage technology. In the present work, a novel large-scale PtH2tP system driven by wind-solar hybrid energy and integrated with HBGTs was proposed and investigated. An economic optimization model was developed to promote the system participation in the electricity-carbon markets, including the spot market, the ancillary service market, and the carbon market. The economic competitiveness of the PtH2tP was assessed under baseline, single ancillary service and multi-market coordination scenarios, taking Shaanxi, China as the case study area. It was indicated that the baseline levelized cost of energy of the proposed PtH2tP without carbon trading was determined as 0.0334 €/kWh. Peak shaving yielded the most significant economic improvement for the system among single ancillary service market participation options, with a 19.46% increase in the internal rate of return from the baseline. In the multi-market coordination scenario, the net present value of the system increased by 68% relative to the baseline when carbon trading was incorporated. These results offered theoretical references for the coordinated optimization of multi-market operations and large-scale deployment of electricity-hydrogen coupling technologies.

Keywords:

Hydrogen-blended gas turbine; Multi-market coordination; Power-to-H_2-to-power system; Electricity-carbon market; Salt cavern hydrogen storage.

1. Introduction

Driven by the rapid advancement of renewable power generation technologies and strong policy support, the installed capacity of renewable energy sources, primarily wind and solar, is growing rapidly, and their share in the global electricity supply is continuously increasing [1]. The application and development of renewable energy are widely recognized as a key strategy for mitigating global environmental challenges and achieving carbon neutrality goals [2]. However, wind and solar are characterized by randomness, intermittency, and uncertainty, which pose significant risks to the safe and stable operation of power grids integrated with large-scale wind and solar, severely restricting the large-scale grid connection and efficient utilization of renewable energy [3]. Consequently, exploring effective energy storage and conversion technologies to enable the flexible dispatch of renewable energy has become a research hotspot in the energy field.

Among various energy storage technologies, hydrogen energy storage has emerged as a promising solution due to its advantages such as large storage capacity, long-duration storage capability, wide application scenarios, and zero carbon emissions during utilization [4, 5]. In terms of energy storage technology selection, single energy storage forms are limited by their own technical characteristics and struggle to meet multi-dimensional system requirements [6]. The power-to-H_2-to-power system (PtH2tP), which integrates renewable power generation, water electrolysis for hydrogen production, hydrogen storage, and hydrogen-to-power conversion, forms a closed loop for the conversion, storage, and regeneration of renewable energy, and is regarded as an effective approach to address renewable energy consumption challenges [7, 8]. Alkaline electrolysis, characterized by its high maturity and reliability, as well as low cost, has become the mainstream technology for large-scale hydrogen production from renewable energy [9]. Meanwhile, hydrogen-blended gas turbines (HBGTs) have garnered widespread attention in the hydrogen-to-power sector due to their good compatibility with existing natural gas power systems, high power generation efficiency, and operational flexibility [10]. Furthermore, underground salt cavern hydrogen storage, as a large-scale physical hydrogen storage technology, offers the advantages of low investment cost and excellent safety. It can effectively match the large-scale hydrogen production and consumption of the PtH2tP system, providing reliable hydrogen storage assurance for the stable operation of the system [11].

In recent years, a series of studies on PtH2tP have been conducted by researchers, with a focus on system configuration optimization, operational strategy design, and techno-economic analysis [12, 13]. Yang et al. [14] proposed a microgrid system integrating PtH2tP with supply-demand coordination strategies and found that the introduction of PtH2tP can specifically address the system operation and consumption challenges caused by the fluctuating and intermittent output of distributed renewable energy, effectively improving the stability and economic efficiency of microgrid system operation. Zhang et al. [13] designed an integrated planning framework for urban PtH2tP, obtaining an optimal economic configuration scheme for the PtH2tP that meets the personalized needs of users. To further improve the power-to-hydrogen-to-power conversion efficiency, Fan et al. [15] designed a wind-hydrogen energy storage system utilizing waste heat, which broke through the functional limitations of traditional wind-hydrogen coupling systems, and effectively explored the system's energy utilization potential. Kumar et al. [16] further considered the participation in the day-ahead electricity wholesale market, reserve market, and hydrogen market, and proposed an energy dispatch method for the electricity-hydrogen coupling system participating in multi-market, which effectively balances the interests of microgrid operators and users. However, existing research has mostly concentrated on the techno-economic performance of PtH2tP in single-market, without in-depth analysis of system operational benefits in the context of the gradual marketization of the power industry [17]. With the deepening of electricity market reform, power systems can participate in various market transactions, including medium- and long-term electricity markets, spot markets, and ancillary service markets, which provides multiple revenue channels for PtH2tP [18 ,19]. It has been widely confirmed by recent studies that the economic break-even of PtH2tP cannot be achieved through participation in a single electricity market alone, while electricity market analysis and carbon market research are treated separately in most existing studies, and the synergistic revenue potential of the two markets is systematically neglected [20]. In current research, the potential of multi-market participation is overlooked, which will lead to inaccurate assessments of the economic benefits of PtH2tP and constrain its market-oriented development.

Furthermore, the carbon emission reduction attributes of the PtH2tP system have not been fully considered in existing studies. Fu et al. [21] developed a dispatch model involving carbon trading costs, energy procurement costs, and wind curtailment costs for an electricity-hydrogen-gas integrated energy system, finding that hydrogen fuel cells can promote the full consumption of renewable energy. The China Certified Emission Reduction (CCER) market, as a vital component of the national carbon market, can convert the carbon emission reduction benefits into economic benefits, which serves as a significant supplement to the income of renewable energy projects [22, 23]. By converting renewable energy into hydrogen and hydrogen into power, the PtH2tP achieves low-carbon energy utilization and demonstrates significant carbon emission reduction effects [24]. Incorporating CCER revenues into the economic analysis framework of the PtH2tP system facilitates a more comprehensive evaluation of its economic benefits. Moreover, the selection of case study regions in existing PtH2tP system research often shows a lack of adequate consideration of the matching degree among regional renewable energy resources, hydrogen storage geological conditions, and electricity market demand, resulting in poor practical applicability of the research findings [25].

Against this background, a large-scale power-to-H_2-to-power system (PtH2tP) was proposed in the present work. Taking Shaanxi, China as the case study area, a comprehensive economic analysis model of the PtH2tP was established after full consideration of multi-market participation and CCER revenues, and the sensitivity of key market parameters to system economics is further analyzed. This framework not only improves the techno-economic analysis system for electricity-hydrogen coupling systems but also provides a theoretical reference and practical guidance for the large-scale deployment of green hydrogen power generation technology and the coordinated optimization of multi-market operations.

2. Model

2.1. System Overview

Figure 1 shows the schematic diagram of the proposed PtH2tP. The system takes wind and solar renewable energy as the input and consists of four core functional units, including hydrogen production, hydrogen storage, and hydrogen-blended power generation, in which the closed-loop operation of renewable energy power conversion, storage and re-generation can be realized.

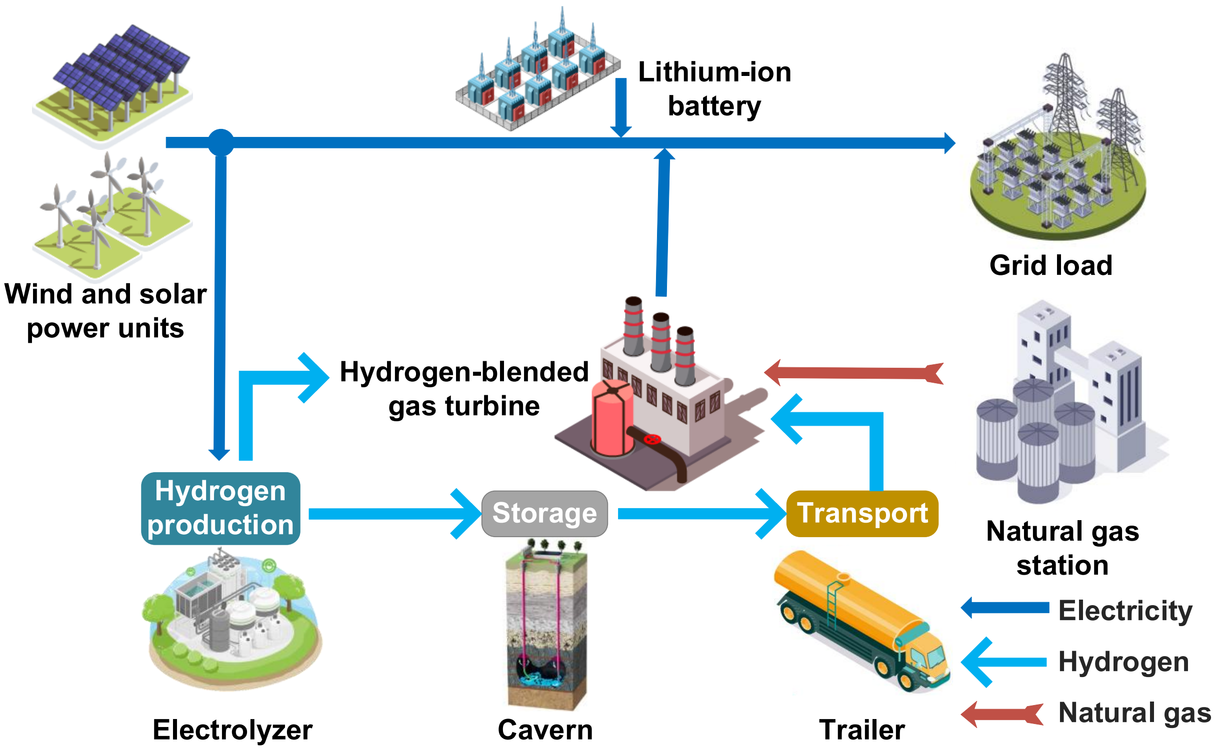

Figure. 1. *Schematic diagram of the proposed PtH2tP.*

2.2. Economic analysis model

In the present work, a comprehensive economic analysis model for PtH2tP that participates in multi-markets covering electricity trading and carbon trading market was constructed. The revenue accounting methods corresponding to each scenario were established, and four core economic evaluation indicators were determined, to provide a quantitative analysis framework for the economic comparison of different market operation strategies.

2.2.1. Revenue model

Based on China's electricity market transaction system, the revenue framework of the PtH2tP constructed in the present work covers three market categories: the medium-and-long-term (MLT) and spot electricity market, the ancillary service market, including peak shaving (PS), frequency regulation (FR) and capacity leasing (CL), and the carbon trading markets.

PtH2tP participates in electricity market transactions through a hybrid mode of MLT price difference contracts being combined with full-quantity spot transactions, and the core revenue derives from peak-valley price difference arbitrage. Energy conversion losses in the whole process of electrolytic hydrogen production, hydrogen storage and hydrogen-blended power generation were fully considered for revenue accounting. The specific revenue calculation is as follows:

$$R_{con} = \sum_{t=1}^{T} p_t^{sm} \cdot p_t^{sal,sm} + \sum_{t=1}^{T} \left(p_t^{ml} - p_t^{sm} \right) \cdot p_t^{sal,ml} - \sum_{t=1}^{T} p_t^{sm} \cdot p_t^{pur,sm} \qquad (1)$$

where R_{con} denotes the annual revenue of the system; p_t^{sm} represents the spot market trading price at time t; $p_t^{sal,sm}$ is the electricity sales volume of the system as the power seller participating in the spot market at time t; p_t^{ml} represents the MLT market trading price at hour t; $p_t^{sal,ml}$ is the electricity sales volume of the system as the power seller participating in the MLT market at hour t; and $p_t^{pur,sm}$ is the electricity purchase volume of the system as the power buyer participating in the spot market at time t.

Ancillary services provided by energy storage mainly include two types: PS and FR. Revenue from peak shaving services has two parts, peak-valley price difference arbitrage and peak shaving compensation fees, which are both directly related to the system's peak shaving capacity (PSC), depth of discharge and annual activation times. The specific revenue calculation is as follows:

$$R_{ps} = \sum_{i=1 \cdots N} P_{ps} \cdot DOD \cdot \beta_{ps} \cdot n_y / \left(1+r\right)^i \qquad (2)$$

where R_{ps} denotes the peak shaving revenue; P_{ps} represents the peak shaving compensation price; DOD is the depth of discharge; β_{ps} represents the benchmark of PSC that can be provided by the system; n_y is the annual activation times; and r is the standard discount rate or benchmark rate of return.

Core revenue of frequency regulation services is frequency regulation capacity (FRC) compensation. This part of compensation was not included in the accounting scope in this study, considering the incomplete capacity compensation policy system in typical cities of China. Revenue measurement was completed based on the system's FRC benchmark, comprehensive FR performance index and annual operation duration, with the focus on the accounting of actual mileage revenue of frequency regulation services. The revenue calculation of auxiliary FR is as follows:

$$R_{fr} = \sum_{i=1\cdots N} n_d \cdot d_y \cdot P_{fr} \cdot \beta_{mil} \cdot K / \left(1+r\right)^i + R_{CCER} \quad (3)$$

where R_{fr} denotes the frequency regulation revenue; n_d represents the equivalent full mileage times of daily operation; d_y is the annual operation day; P_{fr} represents the frequency regulation compensation price; β_{mil} represents the benchmark of FRC that can be provided by the system; and K is the comprehensive regulation performance index.

The system obtains revenue by flexibly leasing its energy storage capacity to the power grid, industrial and commercial users or new energy power stations, based on the shared energy storage operation mode. The revenue level is affected by leasing prices, leasing ratios and local policies. The specific revenue calculation is as follows:

$$R_{cl} = \sum_{i=1\cdots N} \psi \cdot P \cdot K_{cl} / \left(1+r\right)^i \quad (4)$$

where R_{cl} denotes the capacity leasing revenue; ψ represents the leasing ratio; and K_{cl} is the leasing price.

The PtH2tP participates in the national voluntary carbon trading market, realizing the quantification and value conversion of carbon emission reduction benefits by declaring CCER projects. CCER revenue is calculated based on the life-cycle carbon emission reduction and the CCER market transaction price. The calculation of the CCER revenue of the system is as follows:

$$R_{CCER} = \Delta GHG \cdot P_{CCER} \quad (5)$$

where R_{CCER} denotes the CCER revenue; ΔGHG represents the life cycle carbon emission reduction of the system; and P_{CCER} is the CCER market price.

2.2.2. Economic evaluation indicators

Four typical life-cycle economic evaluation indicators were selected for the economic feasibility evaluation of the PtH2tP, namely net present value (NPV), internal rate of return (IRR), payback period (PBP) and levelized cost of energy (LCOE).

NPV reflects the overall profitability of the PtH2tP throughout its life cycle, within the accounting scope covering the system's initial total investment, annual cash inflows and cash outflows. The time value of funds is fully considered in the measurement process, reflecting the net profit level of the project at a specific discount rate. The calculation formula is:

$$NPV = \sum_{n=0}^{N} C_{I,n}\left(1+r\right)^{-n} - \sum_{n=0}^{N} C_{O,n}\left(1+r\right)^{-n} \quad (6)$$

where $C_{I,n}(1+r)^{-n}$ represents the cash inflow in the nth year; $C_{O,n}(1+r)^{-n}$ represents the cash outflow in the nth year; and N denotes the service life of the system.

IRR is a symbol of the actual investment return level of the PtH2tP and defined as the discount rate making the net present value of the project zero over its entire life cycle. It directly reflects the feasibility and profit margin of system investment, serving as a core indicator for judging the economic attractiveness of the project. The formula of the IRR is:

$$NPV = \sum_{n=0}^{N} C_{I,n}\left(1+IRR\right)^{-n} - \sum_{n=0}^{N} C_{O,n}\left(1+IRR\right)^{-n} = 0 \quad (7)$$

PBP refers to the time required for PtH2tP to recover its initial total investment, calculated based on the cumulative net cash flow of the system in each year. It reflects the investment recovery efficiency and cash flow performance of the project, as an important indicator for evaluating the short-term economic risks of the PtH2tP. The formula is as follows:

$$NPV=\sum\nolimits_{n=0}^{PBP}C_{I,n}\left(1+r\right)^{-n}-\sum\nolimits_{n=0}^{PBP}C_{O,n}\left(1+r\right)^{-n}=0 \quad (8)$$

LCOE accounting covers all cost items, including initial investment, operation and maintenance, and energy conversion losses, which can accurately reflect the cost competitiveness of the system in terms of per unit power generation. For the system, the cash inflow includes the electricity revenue from discharged electricity and revenue from other sources, which can be expressed as:

$$C_{I,n}=A_n\cdot P_{ele}+B_n \quad (9)$$

where A_n represents the on-grid discharged electricity in the nth year; P_{ele} is the on-grid electricity price of discharged electricity; and B_n represents the revenue from other sources in the nth year.

The electricity price of discharged electricity that makes the NPV zero is the life cycle LCOE of the energy storage system. Its meaning is the ratio of the NPV of the difference between the total life cycle expenditure cost and other income sources to the time value of the output electricity, which is calculated as:

$$LCOE=P_{ele}=\frac{\sum_{n=0}^{N}\left(C_{O,n}-B_n\right)\left(1+r\right)^{-n}}{\sum_{n=0}^{N}A_n\left(1+r\right)^{-n}} \quad (10)$$

In the present work, the mathematical modelling of PtH2tP was completed based on the MATLAB R2022b platform. With the minimization of the system LCOE as the optimization objective and the installed capacity of wind turbines (WTs), photovoltaics, batteries, electrolyzers and HMGTs as the optimization variables, the genetic algorithm was adopted to solve the mixed integer linear programming problem. The key parameters were set as follows: population size, crossover probability, mutation probability and maximum iteration number were 100, 0.8, 0.1 and 200, respectively.

3. Results and discussions

In the present work, Shaanxi Province, which has excellent wind-solar and salt cavern hydrogen storage resources as well as urgent demand for power grid peak shaving services, was taken as the case study, and the revenue model and economic performance of PtH2tP in the local electricity market were focused on. Firstly, the revenue characteristics of the system participating in the MLT and spot markets (i.e., the baseline scenario) were analysed. Secondly, the revenue performance of the system participating in various ancillary service markets under the baseline scenario was investigated. Finally, the economic performance of the system after multi-market coordination was explored, and the economic optimization potential of the carbon trading mechanism in this scenario was additionally verified.

3.1. Revenue analysis of PtH2tP in medium-and-long-term and spot markets

Prior to the revenue analysis of the PtH2tP system under the baseline scenario, the operational boundary conditions should be clarified first. The system is assumed to supply power to a certain region in Shaanxi, and the annual electricity load profile of this region is displayed in Figure 2. In a typical year, the regional electricity load fluctuated between 130 and 330 MW, with the highest peak and the largest fluctuation amplitude occurring in June and December. The market transaction prices are determined with reference to the actual trading prices in the baseline scenario. The remaining key techno-economic parameters of the system are listed in Table 1.

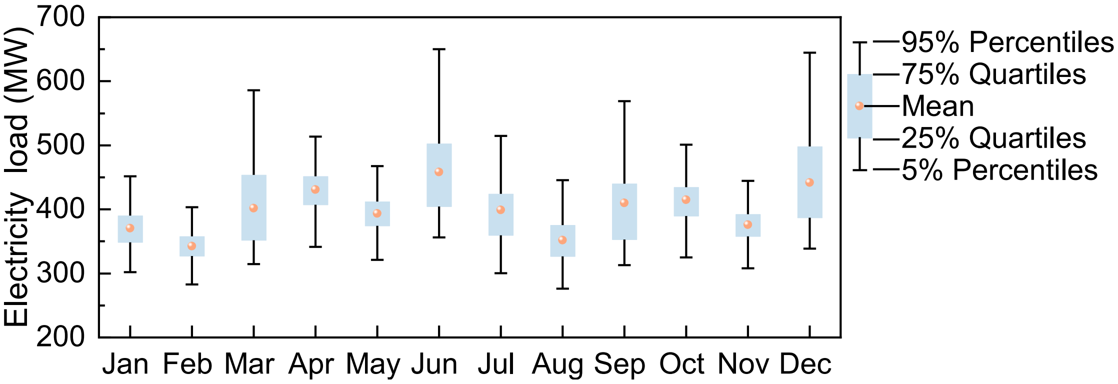

Figure. 2. *Annual electricity load curve of a typical year in a region of Shaanxi.*

Table 1. *Key technical parameters and investment costs [19].*

Item	Value
Installed cost of wind components, €/kW	873.06
Installed cost of photovoltaic components, €/kW	594.06
Safe state of charge of the battery, %	20-90
Installed cost of the battery, €/kW	258.66
Installed cost of the electrolyzer components, €/kW	423.64
Package higher heating value efficiency, %	70.95
Package lower heating value efficiency, %	60.03
Storage pressure of salt cavern, bar	60-150
Investment cost of salt cavern, €/kg H_2	0.26

Figure 3 depicted the electricity spot market prices in Shaanxi Province over a typical year. To offset the impact of load fluctuations on the execution of MLT contract execution, a monthly contract trading scheme is adopted in the present work, where market participants submitted typical daily power curves monthly, as shown in Figures 4. The system operating power ranged from 300 to 350 MW on the typical day of this month, and the operating power during 12–24h is significantly higher than that in the first 12h. In addition, the MLT market price peaked at the 7th and 20th hours and reaches the trough during 13–14h on the typical day, with the electricity price fluctuated from 19 to 73 €/MWh.

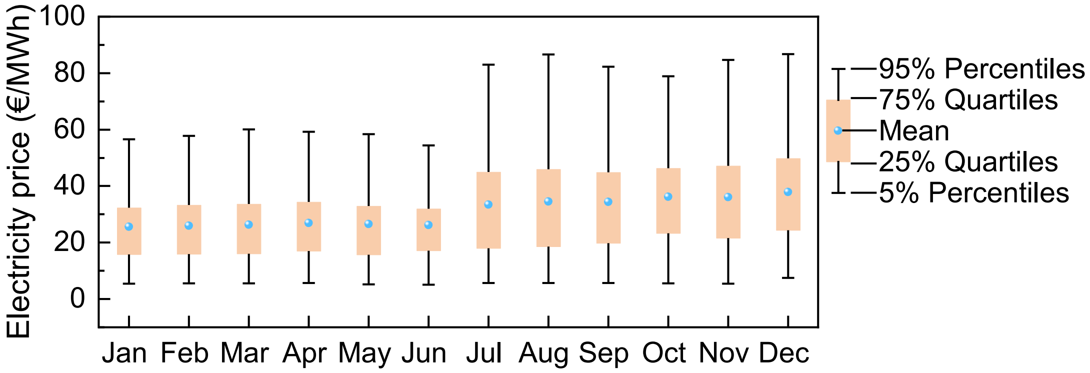

Figure. 3. *Electricity price in the spot market over a typical year.*

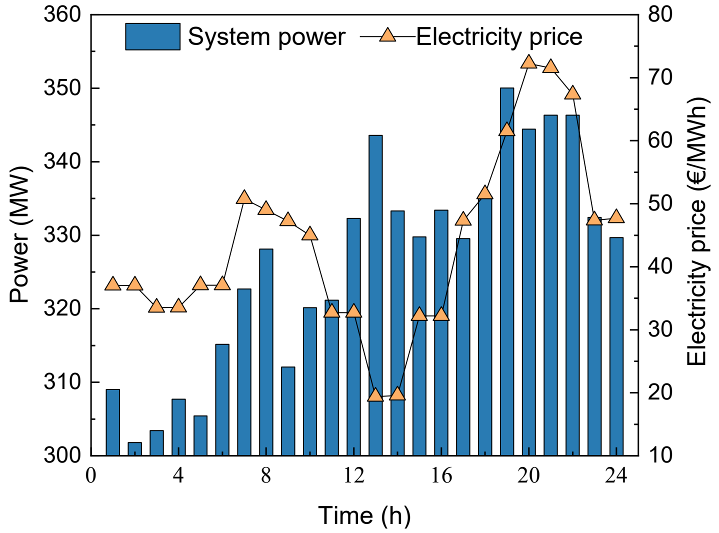

Figure. 4. *Typical daily awarded power and price curves participating in the MLT electricity market.*

The capacity configuration and economic performance of the PtH2tP under the baseline scenario are shown in Table 2. The system is configured with a WT of 618 MW and alkaline electrolyzers of 120MW. The renewable energy utilization rate reached 98.31%, with an LCOE of 0.0334 €/kWh and an IRR of 12.18%. As shown in Figure 5, the initial investment of WT accounted for the highest proportion of the total at 76.4%, followed by that of HBGTs and electrolyzers in sequence. Hydrogen accumulation raises higher requirements for the scale of hydrogen storage facilities. The investment in salt cavern hydrogen storage only accounted for 1.8% of the total system investment. Due to its low-cost feature, the adverse impact of hydrogen accumulation on the system's economic performance is effectively mitigated. As shown in Figure 6, the carbon emissions of the system originate from purchased grid power and HBGTs operation. The carbon emissions from purchased grid power accounted for 58.6% of the total ones. HBGTs ranked second in carbon emission contribution. Emissions from its fuel consumption and manufacturing process accounted for 26.3% and 3.3% of the total amount, respectively.

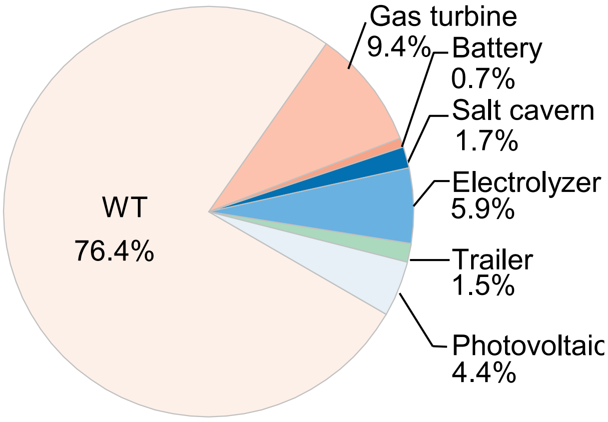

Figure. 5. *Initial investment distribution under the baseline scenario.*

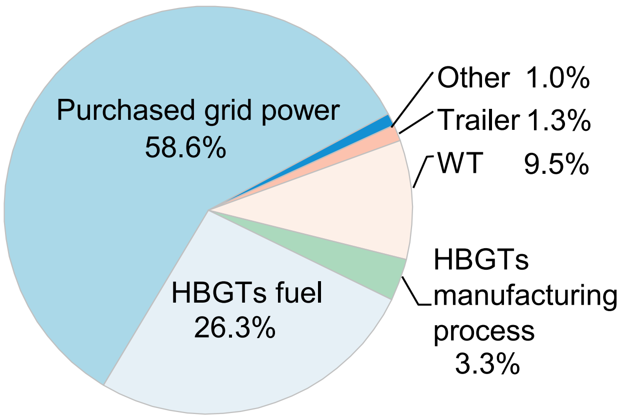

Figure. 6. *Carbon emissions distribution under the baseline scenario.*

Table 2. *Capacity configuration and economic performance of PtH2tP under the baseline scenario.*

Item	Value	Item	Value
WT, MW	618	NPV, M€	494.71
Photovoltaic, MW	11	IRR, %	12.18
Lithium-ion battery, MW	25	PBP, yr	4.67
Alkaline electrolyzer, MW	120	LCOE, €/kWh	0.0334
Hydrogen-blended gas turbine, MW	198	Initial investment, M€	235
Renewable energy utilization rate, %	98.31		

3.2. Comparative analysis of PtH2tP revenue in ancillary service markets

The revenue performance of the system participating in three types of ancillary service markets, namely FR, PS, and CL market, is further analysed. Relevant parameters are sourced from official policies, actual market data, and published studies [26-28]. Economic performance of the PtH2tP in ancillary service markets is shown in Figure 7. The results showed that the system achieved better economic performance with peak shaving service participation under the baseline scenario, compared with the other ancillary service markets. The annual peak shaving service revenue reaches 22.18 M€. The IRR increases by 19.46% from the baseline. The economic performance of the PtH2tP in ancillary service markets after the consideration of carbon trading revenue is shown in Figure 8. The economic performance ranking of the system remained unchanged after consideration of carbon trading revenue gained in CCER market. capacity leasing services yielded the lowest economic performance. The CCER revenue of the system after peak shaving service participation increases by 5% from the baseline.

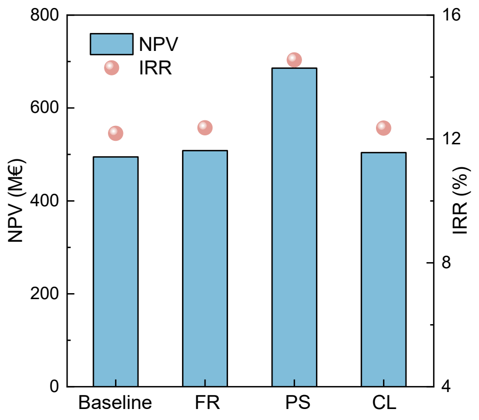

Figure. 7. *Economic performance in ancillary service markets.*

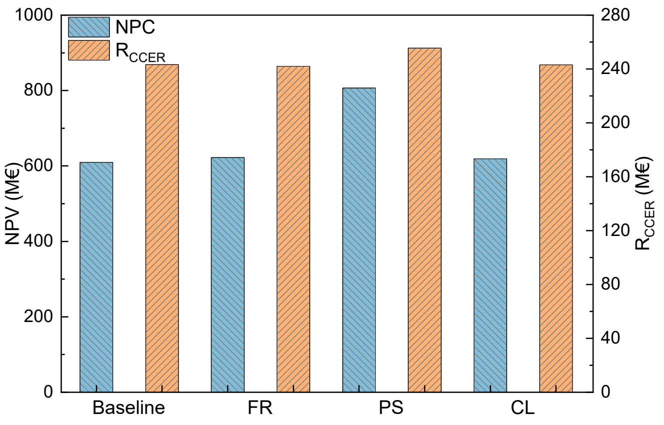

Figure. 8. *Economic performance in ancillary service markets after consideration of carbon trading.*

Key parameters directly affect the revenue level and cost-effectiveness of market participants in services such as frequency regulation and peak shaving. Figure 9 showed change rate in NPV of PtH2tP with the variation of ±20% in key parameters. When participating in the electricity market, the NPV of the system increased significantly with the increase of MLT electricity market price and PS compensation price successively. A 10% increase in the MLT market price led to a significant increase of 29.6% in the NPV of the system. In addition, the impacts of FRC compensation price, comprehensive frequency regulation performance index (CFRPI), capacity leasing price and capacity leasing rate were relatively low, causing a 0.1%-0.9% increase in the system NPV with every 10% increase in these parameters.

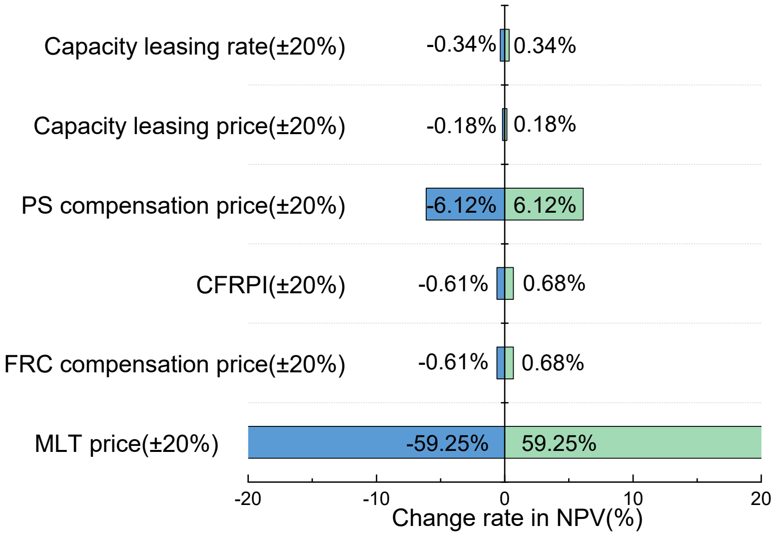

Figure. 9. *Sensitivity analysis of key parameters of PtH2tP.*

3.3. Economic performance of PtH2tP under multi-market coordination

Based on the research on PtH2tP participating in a single ancillary service market, the economic performance of the system participating in multi-market coordinated operation was further explored. In the present work, the maximization of the NPV of PtH2tP in life cycle was taken as the optimization objective, to improve the comprehensive economic benefits of the system through multi-market coordinated participation. As a key energy storage technology in PtH2tP, the battery energy storage system participated in three types of ancillary service markets: FR, PS and CL markets simultaneously, which requires reasonable capacity allocation to achieve the optimal economic performance of the system. For this reason, the optimization variables of the decision model include reserved FRC, reserved PSC of the PtH2tP main body, and battery leasing ratio. The mixed integer linear programming method was adopted in the model, and the algorithm was solved through the MATLAB platform.

3.3.1. Revenue analysis of PtH2tP with multi-market participation

The capacity allocation and economic performance results of the system after multi-market coordination are shown in Table 3. The battery leasing rate of the system was maintained at 80%, and the annual PSC and FR mileage reached 6.09×10^5 MWh and 53.77×10^4 MW respectively. HBGT was the main force of frequency regulation services, and its FR mileage accounted for 89.73% of the total FR mileage. Compared with ones of the system participating in a single ancillary service market, the FR mileage of the system showed a downward trend, the PSC was slightly adjusted, and the battery leasing capacity remained stable. In terms of revenue, the total annual revenue of the system in the ancillary service market after using the coordination strategy reached 24.16 M€, which exceeded the sum of its revenue in three single ancillary service markets. From the perspective of revenue structure, peak shaving services contributed the most to the coordinated market revenue, followed by frequency regulation services of HBGTs and battery capacity leasing services, which also confirmed the configuration rule that the priority of battery participation in capacity leasing services in the system was higher than that of peak shaving and frequency regulation services. Compared with the economic optimization benefit of the system in the baseline scenario, it was significantly improved after using the multi-market coordination strategy, with NPV increasing by 43.61%, the IRR being increased to 14.91%, and the PBP being shortened to 3.53 years, which fully reflected the improvement effect of multi-market coordinated operation on the market-oriented operation benefit of the electricity-hydrogen coupling system.

The aforementioned analysis has verified the significant economic superiority of the multi-market coordinated operation strategy for the PtH2tP. To further reveal the intra-day operation characteristics of the system under this optimal strategy and clarify the ancillary service capacity allocation rules of each core equipment, the reserved ancillary service capacity curve of the PtH2tP on a typical day in the multi-market coordinated scenario was analyzed, with the results shown in Figure 10. As shown in Figure 10(a), the HBGT participated in the ancillary frequency regulation service only from 18:00–20:00 and operated in accordance with the baseline power generation strategy for the rest of the time. As shown in Figure 10(b), the battery provided frequency regulation service for 10 hours in the ancillary FR market, with an average reserved capacity of 2 MW. As shown in Figure 10(c), the 20 MW energy storage battery participated in the CL market through an annual long-term contract. The reserved PSC is presented in Figure 10(d). The system participated in both peak clipping and valley filling services on this typical day: it absorbed surplus grid power from 1:00-5:00 for valley filling and supplied power to the grid during the high-load period from 11:00-14:00 for peak clipping.

Table 3. *Capacity allocation and economic performance under multi-market coordination*

Item	Baseline	PS	FR	CL	Multi-Market
Battery leasing rate, %	/	/	/	80	80
PSC, 10^5 MWh/yr	/	6.11	/	/	6.09
Battery FR mileage, 10^4 MW/yr	/	/	16.30	/	5.52
HBGT FR mileage, 10^4MW/yr	/	/	57.41	/	48.25
Total ancillary market revenue, M€/yr	/	22.18	1.34	0.48	24.16
NPV, M€	494.71	685.85	508.08	503.90	710.48
LCOE, €/kWh	0.0334	0.0340	0.0336	0.0333	0.0339

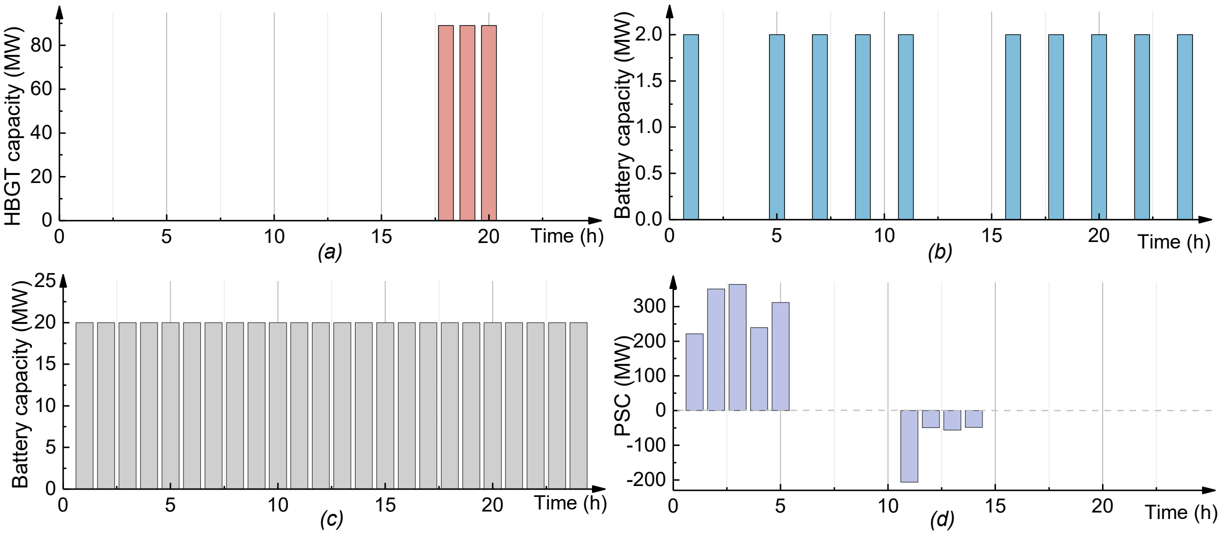

Figure. 10. *Reserved ancillary service capacity of the PtH2tP on a typical day: a) reserved FRC of the HBGT, b) reserved FRC of the battery, c) leasing capacity of the battery, d) reserved PSC.*

Figure 11 illustrated the reserved PSC of each system component on a typical day under the multi-market coordination strategy. The peak shaving service is dominated by flexible regulations, followed by electrolyzers, with negligible battery contribution. HBGTs only provide negative peak-shaving on the 11th. Positive peak shaving service is provided at 1:00-5:00, while negative peak shaving service occurs at 11:00-14:00; no peak shaving service is offered in other periods. Figure 12 showed the system operation curve on the typical day. WTs are the main power generation unit with small supplementary PV support, and the electricity load ranges from 350 to 400 MW. Electrolyzers operate for hydrogen production at 2:00-5:00 and provide negative peak-shaving at hours 12:00–14:00. Batteries maintain slight charge-discharge cycles, and purchased power is used at multiple hours for power balance. HBGTs generate power at hours 6, 8, 11 and 18–22, and reserve FRC at hours 19–23, with the FR opportunity cost being the additional fuel consumption of HBGTs.

3.3.2. Economic variation law of PtH2tP under electricity-carbon coordination

After the introduction of carbon trading, the reserved ancillary service capacity of the system after using the coordination strategy remained unchanged. The reason for this phenomenon is that the difference in CCER revenue brought by the system participating in various single ancillary service markets is small, which has a low impact on the overall optimization effect of the system capacity configuration. Even when the system capacity configuration remained unchanged, the electricity-carbon coordination still brought significant economic improvement to the system. As shown in Table 4, the IRR of the system significantly increased to 16.35%, and the NPV increased by 68% from baseline. In summary, the electricity-carbon coordination strategy realizes the conversion of carbon revenue through CCER application and can significantly improve the economic competitiveness of PtH2tP without adjusting the original ancillary service capacity configuration, which reflects the important value of electricity-carbon coordinated operation.

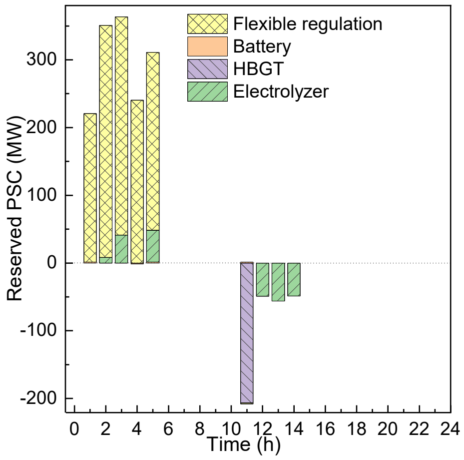

Figure. 11. *Reserved PSC curve of each system component on a typical day.*

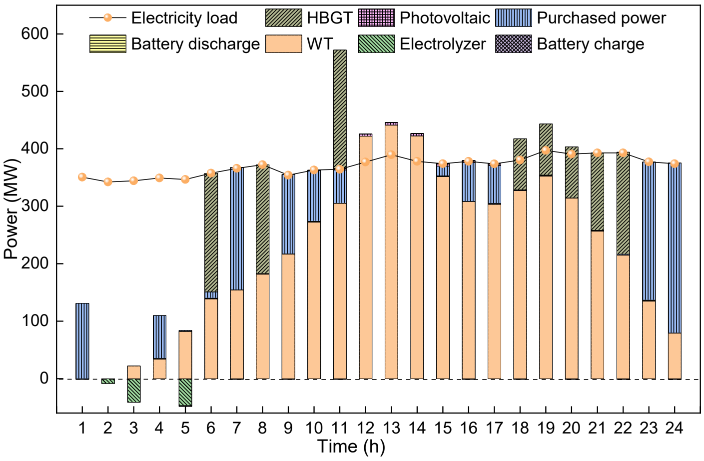

Figure. 12. *System operation curve on a typical day.*

Table 4. *Optimization results and economic performance under electricity-carbon coordination.*

Item	Baseline	Electricity-Carbon Coordination
CCER revenue, M€	/	255.16
NPV, M€	/	831.24
LCOE, €/kWh	0.0334	0.0339
IRR, %	12.18	16.35
PBP, yr	4.67	3.11

4. Conclusions

Against the backdrop of electricity marketization, the revenue stability and operational feasibility of renewable energy systems hinge on coordinated participation in electricity and carbon markets. Nevertheless, the inherent intermittency and volatility of wind and solar power severely restrict the large-scale grid integration of renewable energy. As an effective technical solution for renewable energy consumption and grid integration, the PtH2tP system demonstrates significant application potential. In this work, a wind-solar hybrid-driven PtH2tP system integrated with HBGTs, and salt cavern hydrogen storage was proposed, and a comprehensive techno-economic analysis was performed with Shaanxi Province, China as the case study region. The main conclusions were drawn as follows:

- The PtH2tP presented favorable economic competitiveness in the baseline scenario involving MLT and spot markets. The system's renewable energy utilization rate reached 98.31%, with an LCOE of 0.0334 €/kWh and an IRR of 12.18%. The investment cost of the salt cavern hydrogen storage module was 0.26 €/kg H_2, which accounted for only 1.8% of the total initial investment, and the economic pressure of large-scale hydrogen storage was effectively mitigated by this low-cost advantage.
- Multi-market participation and electricity-carbon coordination could significantly improve the economic performance of PtH2tP. Among single ancillary service markets, peak shaving services delivered the best economic improvement, annual peak shaving services revenue was 22.18 M€ and the system's IRR increased by 19.46% compared to the baseline; its superiority remained unchanged even after incorporating carbon trading, meanwhile CCER revenue rose by 5% relative to the baseline. In multi-market coordinated operation, the system's NPV grew by 43.61% compared to the baseline. Further integrating carbon trading enabled the IRR to increase to 16.35% and the PBP to be shortened to 3.11 years without adjusting the original capacity configuration, which fully verified the significant value of electricity-carbon synergy in enhancing the system's economic competitiveness.
- Market parameters exerted distinct impacts on the economics of the PtH2tP participation in ancillary services, with the MLT electricity market price as the core influencing factor. A 10% increase in the MLT electricity market price led to a 29.6% growth in the system's NPV. The PS compensation price was the second most impactful factor, while FR-related and CL-related parameters exerted negligible impacts. This finding indicated that the optimization of MLT electricity price and PS compensation policies was the key to promoting the market-oriented development of the PtH2tP.

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Nomenclature

Letter symbols:

A_n	on-grid discharged electricity in the nth year, kWh
B_n	revenue from other sources in the nth year, €
CCER	China Certified Emission Reduction
$C_{I,n}$	cash inflow in the nth year, €
CL	capacity leasing
$C_{O,n}$	cash outflow in the nth year, €
DOD	depth of discharge
d_y	annual operation days, d
FR	frequency regulation
FRC	frequency regulation capacity, MW
HBGT	hydrogen-blended gas turbine
IRR	internal rate of return, %
K	comprehensive regulation performance index
Kcl	leasing price, €/kW
LCOE	levelized cost of energy, €/kWh
MLT	medium-and-long-term
n_d	equivalent full mileage times of daily operation
N	service life of the system, yr
NPV	net present value, M€
n_y	annual activation times
P	price, €
PBP	payback period, yr
PSC	peak shaving capacity, MWh
p_t^{ml}	medium-and-long-term market trading price at time t, €/kWh
$p_t^{pur,sm}$	electricity purchase volume of the system as the power buyer in spot market at time t, kWh
$p_t^{sal,ml}$	electricity sales volume of the system as the power seller in medium-and-long-term market at time t, kWh
$p_t^{sal,sm}$	electricity sales volume of the system as the power seller in spot market at time t, kWh
p_{sm}	spot market trading price at time t, €/kWh
PS	*peak shaving*
r	standard discount rate or benchmark rate of return, %
R	revenue, M€

Greek symbols:

ΔGHG	life cycle carbon emission reduction of the system, tCO$_2$
β_{mil}	benchmark of frequency regulation mileage that can be provided by the system, MW
β_{ps}	benchmark of peak shaving capacity that can be provided by the system, MWh
ψ	leasing ratio, %

Subscripts and superscripts:

cl	capacity leasing market
con	system comprehensive
ele	discharged electricity, kWh
fr	frequency regulation market
mil	frequency regulation mileage
ml	medium-and-long-term market
n	nth year
ps	peak shaving market
pur	electricity purchase
sal	electricity sales
sm	spot market
t	specific time

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