PROCESS MODELING AND ECONOMIC VIABILITY ANALYSIS OF A POWER-TO-H_2-TO-POWER SYSTEM: CASE STUDY IN CHINA

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ABSTRACT

The power sector generates the most significant greenhouse gas emissions in many countries, while renewable energy penetration faces a bottleneck due to its volatility. Therefore, it is imperative to make substantial efforts to promote the penetration of renewable energy sources into the power grid. The process of hydrogen production with renewable energy sources is becoming increasingly economical as the cost of renewable energy sources, particularly onshore wind, has fallen dramatically. In the present work, a power-to-H_2-to-power system (PHPS) combining onshore wind power was proposed as a solution for high penetration of renewable energy, which incorporates a large-scale alkaline water electrolyzer, and a gas turbine. A techno-economic study based on NOVO PRO© and GT PRO was carried out and applied to cases in Shaanxi, China. The performance and operational characteristics of two types of PHPS with different hydrogen storage methods, PHPS/Tank and PHPS/Cavern, were compared. It is indicated that when 30% of the fuel of the gas turbine was replaced by hydrogen, the levelized cost of energy (LCOE) of the PHPS/Cavern was 0.0498 €/kWh with an internal rate of return (IRR) of 6.41%, therefore, PHPS/Cavern was economically feasible in China. Moreover, the renewable energy utilization and carbon reduction benefits of the PHPS were significant. The surplus electricity (curtailed electricity) and carbon emissions of the PHPS/Cavern can be decreased by 52% and 12%, respectively, compared to those of PHPS without hydrogen as the energy carrier. The performance of PHPS with different hydrogen substitution ratios was analyzed. Parametric analysis was further conducted to investigate the influence of key parameters on the system performance, including wind modules investment, electrolyzer investment, transport distance, and electricity price. Finally, under the future scenarios in China in 2050, the LCOE of PHPS/Cavern can be reduced by 15% as well as the IRR increased by 66%. The results implied that the PHPS can be adopted as a viable and low-carbon replacement for conventional peaking generators. The research could provide insights into the synergistic development of green hydrogen for the power sector.

1 INTRODUCTION

In recent years, the large consumption of fossil energy has resulted in serious environmental pollution. Strong support for the development of renewable energy can effectively address these challenges (Wang *et al*., 2023). However, the high penetration of renewable energy sources presents problems associated with energy consumption and the safe operation of the grid (Han *et al*., 2023). Hydrogen energy has several advantages, including abundant sources, high calorific value, efficient conversion to other forms of energy, and the product without any harmful emissions (only water), which is recognized as a clean

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energy source (Huang *et al*., 2023). Hydrogen energy is gradually becoming an important link to promote the clean and efficient utilization of traditional fossil energy and support the large-scale development of renewable energy (Yue *et al*., 2021). In addition, hydrogen energy can be efficiently and rapidly converted into electricity relying on devices such as gas turbines or fuel cells (Staffell *et al*., 2019). Currently, hydrogen fuels in the power sector currently account for less than 0.2% of the global electricity generation mix (IEA, 2023). It is attracting worldwide interest to investigate integrated energy systems with hydrogen as the energy carrier (Hosseini and Wahid, 2016; Fang *et al*., 2024).

The economic benefits of hydrogen production with renewable energy sources have increased significantly as the cost of renewable energy has fallen dramatically (Glenk and Reichelstein, 2019). A large number of researchers have studied the economic costs and future development of hydrogen-related technologies (Zheng *et al*., 2024; Abdin *et al*., 2022). The economic cost of offshore wind hydrogen production technologies was investigated by Luo *et al*. (2022), after alkaline (ALK) water electrolysis, proton exchange membrane (PEM) water electrolysis, and solid oxide water electrolysis being considered. Various hydrogen storage and transportation technologies were discussed by Reuß *et al*. (2017) and Ma *et al*. (2023). The results of Reuß *et al*. (2021) demonstrated that gaseous hydrogen was more convenient for transportation over short distances, while liquid hydrogen was appropriate for transportation in the distances over 130 km. Moreover, a cost-analytical model of hydrogen production from wind power was constructed to investigate its potential in the future (Zhang *et al*., 2023). It is expected that by 2060, hydrogen from wind power could substitute 76.72-92.01 million tons of grey hydrogen in China. Furthermore, ALK and solid oxide electrolyzers were cost-effective alternatives in 2030 (Lin *et al*., 2021).

Various combinations of hydrogen production and storage solutions have been investigated. Stöckl *et al*. (2021) analyzed four hydrogen supply options of filling stations in Germany and provided recommendations related to balancing energy efficiency and time flexibility in the power sector. A planning methodology of hydrogen production for power generation with different technologies and storage units was proposed (Serrano-Arévalo *et al*., 2023). Furthermore, an integrated energy system utilizing underground hydrogen storage coupled with other hydrogen-related technologies was proposed, taking the cases in three typical regions in China as example (Qiu *et al*., 2020). The proposed system can reduce costs as well as achieve emission reductions.

Several researchers have considered fuel cells or gas turbines as hydrogen energy conversion devices. Javadi *et al*. (2022) proposed a multi-generation system that can achieve 12.9 MW of power generation, 96.18 kg/s of freshwater production, and 5.2 kg/s of hydrogen production. Öberg *et al*. (2022) developed an optimization model for evaluating hydrogen production, hydrogen storage, and gas turbines power generation, investigating the techno-economic characteristics of gas turbines in current and future scenarios. Escamilla *et al*. (2022) found that the round-trip efficiency of the power-to-H_2-to-power system could be boosted up to 40%, due to the huge improvement possibility in hydrogen production and power generation. Moreover, the application of renewable hydrogen in combined heat and power systems was investigated, at the same time, the efficiency, levelized cost of energy (LCOE), and carbon emissions (CE) of power plants at different fossil fuel substitution rates were analyzed (Skordoulias *et al*., 2022). A combined wind-photovoltaic-salt cavern energy system, employing fuel cells as the energy conversion system and hydrogen as energy carrier, was proposed by Wu et al. (2023). In addition, the life-cycle impact emissions associated with the power-to-H_2-to-power system were investigated by Song *et al.* (2023). The results indicated that the greenhouse gas and NOx emissions of the system ranged from 8.8 to 366.1 g CO_2eq/kWh and 0.06 to 2.29 g/kWh, respectively. There is a lack of power-to-H_2-to-power systems coupling gas turbines, especially in China, where onshore wind power is cost-effective.

Therefore, a power-to-H_2-to-power system (PHPS) was proposed in the present work to bridge the knowledge gap in this field. Electrolyzers, gas turbines, and batteries were considered as energy conversion systems. The application of the PHPS system in current and future scenarios in Shaanxi, China was analyzed. In addition, different hydrogen substitution ratios and parameter sensitivities were

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discussed.

2 METHOD AND DATA

In order to conduct an economic analysis of PHPS using onshore wind power, the model depicted in Figure 1 was developed using NOVO PRO© software. NOVO PRO© is a publicly available software developed by Thermoflow Inc. for the design, simulation, and optimization of microgrid systems with the aim of minimizing emissions or maximizing profits. The application of PHPS in Yulin, Shaanxi Province, was simulated by NOVO PRO©. The load profiles of a typical area were obtained through field investigations (Figure 2). PHPS consisted of six components in the PHPS, including wind module, lithium-ion battery, electrolyzer, hydrogen transport module, storage module, and gas turbine. The transport and storage modules were not simulated separately in NOVO PRO©.

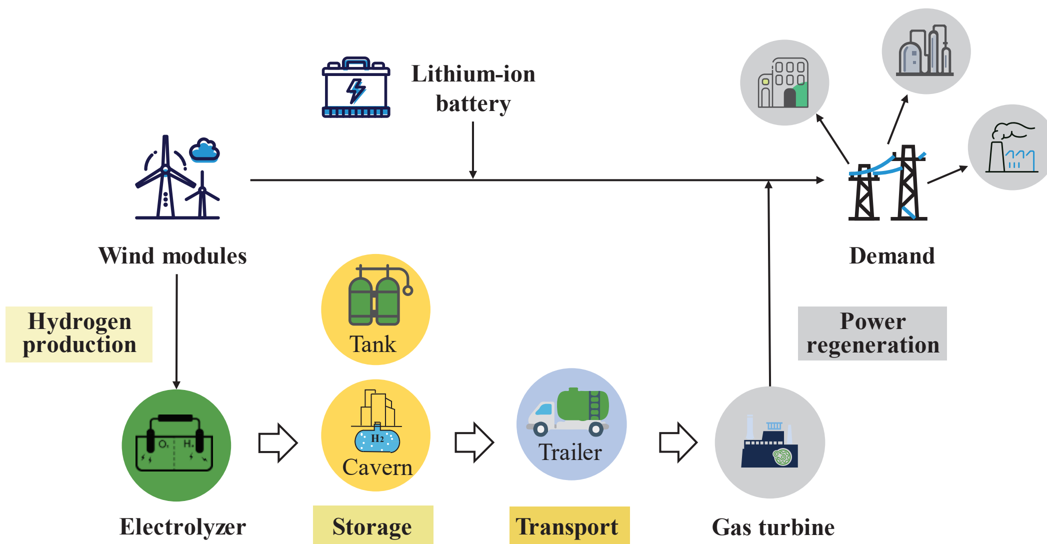

Figure 1: Designed configuration of PHPS

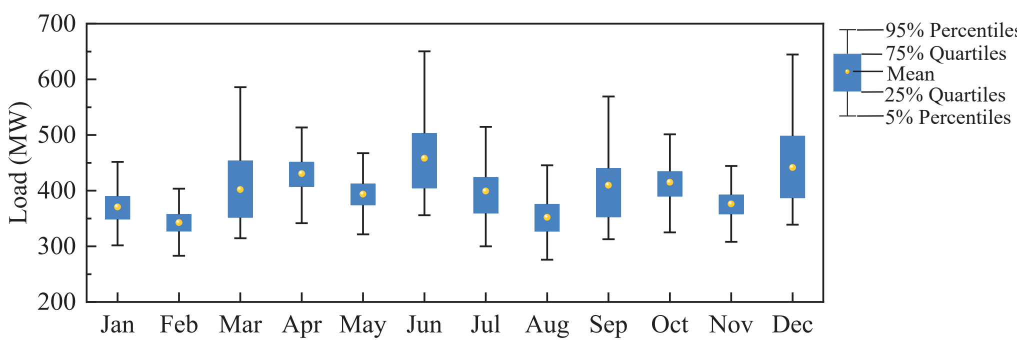

Figure 2: Annual electrical load profiles for the cases studied in the present work

2.1 Wind Module

The initial wind array size was based on the peak load demand and the capacity factor of wind turbine. It was assumed that the wind turbine rows were arranged in a straight line with a spacing of 6 times the diameter of the turbine. The angle of the wind array depends on the amount of the wind resources at the location of the Shaanxi wind farm. The wind array data used in the simulation is given in Table 1. The installed cost of wind components was set to 835 €/kW.

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Table 1: Wind modules data (IRENA, 2023; Chen *et al*., 2024; Thermoflow, 2024)

Items	Values
Capacity	900 MW
Type	GW140/3000
Turbine spacing along rows	6 diameters
Installed cost	835 €/kW
Cost of operation and maintenance	9.25 €/kW/yr

2.2 Lithium-ion Battery

The battery considered in the present work was a lithium-ion battery with an energy density of 185 Wh/kg. The capacity of the lithium-ion battery was set at 100 MWh. The safe state of charge of the battery was between 20% and 90%. In the battery module, the effect of temperature variations was considered. It was assumed that a heating, ventilating, and air conditioning (HVAC) system was used to avoid overheating and overcooling of the battery. Moreover, the average price of the battery module was selected to be 274 €/kWh, and the operation and maintenance cost was estimated to be 4.62 €/kW/yr (Rayit *et al*., 2021).

2.3 Electrolyzer

The initial electrolyzer size was based on the wind power generation and load requirements. ALK and PEM water electrolyzers are common large-scale electrolysis systems (Stöckl *et al*., 2021). ALK water electrolyzers have the advantages of low equipment cost, long lifetime, and mature technology, while PEM electrolyzers have excellent operating characteristics, small size, and low operation and maintenance costs. Currently, ALK and PEM water electrolyzers have been commercialized. However, PEM water electrolyzer lacks competitiveness in China. Therefore, the type of electrolyzer used in PHPS was set as ALK electrolyzer. The pure hydrogen production rate of the electrolyzer module was 90 kg/hr with higher heating value (HHV) and lower heating value (LHV) efficiencies of 70.95% and 60.03% respectively. The hydrogen supply mode of PHPS was used: surplus power was utilized for hydrogen production when there was sufficient wind power generation. The produced hydrogen was supplied via a gas turbine during periods of insufficient wind power. In addition, there was no electricity purchased from the grid for hydrogen production. The installed cost of the electrolyzer components was assumed as 366 €/kW, and the annual operation and maintenance cost was assumed to be 4.3% of the total cost of the system. The data of the electrolyzer is shown in Table 2.

Table 2: Electrolyzer modules data (Huang and Balcombe, 2024; Zhang *et al*., 2023; Thermoflow, 2024)

Items	Values	Items	Values
Capacity	190 MW	H_2 outlet stream temperature	303.15 K
Hydrogen delivery pressure	150 bar	H_2 outlet stream relative humidity	100%
Pure hydrogen production rate	90 kg/hr	Minimum load	5%
Package HHV efficiency	70.95%	Installed cost	366 €/kW
Package LHV efficiency	60.03%	Cost of operation and maintenance	15.8 €/kW/yr
H_2 outlet stream pressure	30 bar		

2.4 Transport Module

The selected hydrogen transportation module was trailer transportation. The compressed gas hydrogen is typically transported by a tube trailer, with steel or composite being used as the main materials of tubes. Steel tubes not only have a smaller capacity, but also smaller investment costs compared to composites ones. In the system studied in the present work, only the trailer transportation with steel tube was considered. The cost of trailer transportation is closely related to the transportation distance and possesses a significant advantage in short distances (Reuß *et al*., 2021). The distance of the transportation module was set at 300 km.

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2.5 Storage Module

A key challenge of the storage and transportation of hydrogen is its low density of 0.09 kg/m^3 (Reuß *et al*., 2017). Therefore, the density of hydrogen needs to be further adjusted. Hydrogen storage technologies consist of the ones of compressed hydrogen, liquid hydrogen, combination with metal hydride carriers, and combination with organic carriers. Short distance transportation was investigated in the PHPS. Therefore, the compressed hydrogen storage technologies the most common mode (Song *et al*., 2023), including stored gas-hydrogen storage tanks and salt cavern storage were considered. It was assumed that hydrogen can be stored in tanks and salt caverns without losses. Gas-hydrogen storage tanks had a storage pressure of 15-250 bar and an investment cost of 2.6 €/kg H_2. Salt caverns had a storage pressure of 60-150 bar and its investment cost was set at 0.26 €/kg H_2. Maintenance costs for both storage methods were assumed to be 2% of the investment (Reuß *et al*., 2017, Abdin *et al*., 2022). Furthermore, hydrogen can also be transported directly after production without storage at the production site (Stöckl *et al*., 2021).

2.6 Gas Turbine

The direction of development of hydrogen gas turbines can be divided into two categories, improvement of conventional combustion chambers and design of new hydrogen combustion chambers. Most existing gas turbines that don't need any modification can allow for a hydrogen substitution ratio of at least 30%. Only the additional components needed for connecting the hydrogen storage equipment and the gas turbine are required. When hydrogen substitution ratios are higher than 50%, costs associated with burner and combustion chamber changes need to be considered. In the present work, 30% of the fuel of the gas turbine was replaced by hydrogen (a hydrogen substitution ratio of 30%) in GT PRO software. Temperature-power curves and temperature-fuel consumption curves were obtained in different load conditions, as shown in Figure 3. It was assumed that the gas turbine module consists of two gas turbine plants. All the hydrogen produced in the electrolyzer was utilized in the gas turbines. There was no need to purchase additional hydrogen or expand the hydrogen sales path.

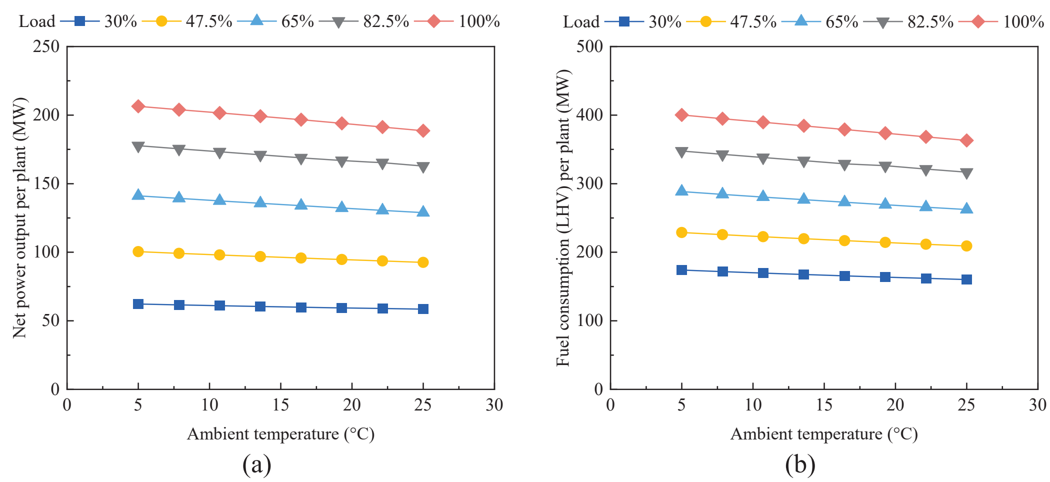

Figure 3: Performance of gas turbine (a) Net power output, and (b) Fuel consumption

3 SIMULATION RESULTS AND DISCUSSIONS

Firstly, PHPS, with a gas turbine assisting the wind turbine in generating electricity to meet the load demand, was simulated using NOVO PRO©. Two types of PHPS with different hydrogen storage methods were analyzed, namely PHPS/Tank, PHPS/Cavern. In the comparison case, the hydrogen equipments were removed and the the hydrogen were not used as the energy carrier (PHPS/without H_2). Renewable energy utilization rate, economic competitiveness, and CEs of the three types of systems were compared.

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3.1 Performance Comparison of PHPS

The annual discount rate of 3% and inflation rate of 3%, and relevant local geographic data of Yulin, Shaanxi were used for simulation. The performance of the three cases is shown in Table 3. The initial investment costs of PHPS/Tank and PHPS/Cavern were 1.15 and 1.13 times higher than that in the PHPS/without H2, respectively. The difference can be traced mainly to the additional investment in the electrolyzer, hydrogen storage, and transportation. In addition, the LCOEs of PHPS/Tank and PHPS/Cavern were 0.0502 €/kWh and 0.0498 €/kWh, respectively, which were 4.5% and 3.7% higher than that of PHPS/without H_2. It is worth noting that although PHPS/Tank and PHPS/Cavern exhibited slightly lower economic performance compared to PHPS/without H_2, they possessed significant advantages in terms of the reduction of renewable energy surplus electricity (SE) and CE. SE of PHPS/Tank and PHPS/Cavern was merely 9.2%, which corresponded to 44.7% of that in PHPS/without H_2. This was primarily attributed to the utilization of excess wind power in the PHPS for hydrogen production. Moreover, gas turbine power generation was the primary source of CE in PHPS/without H_2. CE from gas turbine power generation was significantly reduced by 12% due to the cleanliness of hydrogen when hydrogen was blended with natural gas for power generation. The annual CE was converted to the CE per MWh based on the annual electricity output from the system. The CE per MWh of both PHPS/Tank and PHPS/Cavern was 0.136 t/MWh, which was 17% of that of the average generation mix in China (Han *et al*., 2023). The whole system was dominated by wind power, which was inherently clean. Consequently, PHPS exhibited lower CEs compared to that of the average generation mix in China. The impact of the two hydrogen storage methods on PHPS was further investigated. The operating characteristics and SE of PHPS/Tank and PHPS/Cavern were essentially consistent since the storage and transportation of hydrogen were not directly involved in the electricity generation of PHPS. PHPS/Cavern was more cost-competitive than PHPS/Tank. Further economic analysis of steel tanks and salt caverns revealed that the lower PHPS/Cavern derived mainly from the lower initial investment cost of salt caverns. The initial investment, LCOE, and payback period of PHPS/Tank were about 0-5%, slightly higher than those of PHPS/Cavern.

Table 3: Performance of three cases from different aspects

	PHPS/Tank	**PHPS/Cavern**	**PHPS/without H_2**
Annual electricity revenues (100M€)	1.837	1.837	1.837
Total investment (100M€)	11.129	10.908	9.690
Initial equity (100M€)	3.339	3.273	2.907
Natural gas expense (10M€)	6.116	6.116	6.899
Internal rate of return (IRR) (%)	6.217	6.410	7.255
Payback period (yr)	11.800	11.320	9.566
Net present value (100M€)	1.275	1.432	1.999
LCOE (€/kWh)	0.0502	0.0498	0.0480
SE (% system supply)	9.198	9.198	20.570
Annual CE (0.1Mt)	4.782	4.782	5.400
CE per MWh (t/MWh)	0.136	0.136	0.154

3.2 Investment and Operational Characterization of Equipment

The proportion of investment in each equipment of the PHPS is summarized in Figure 4. Onshore wind modules dominated the investment in all three types of PHPS, with the investment proportion of more than 60% of the total, followed by gas turbines. In PHPS/Tank, the investment proportion of electrolyzer was 8.7%, which ranked third among all equipment investment proportions. In addition, batteries, hydrogen storage modules, and transport modules contributed 2%-2.5%. The investment of the hydrogen storage module of PHPS/Cavern only accounted for 0.2% of the total investment, which was lower than that of PHPS/Tank, while the proportion of the other modules was roughly similar to that of PHPS/Tank.

PHPS/Cavern was taken as a benchmark to further analyze the operational characteristics of PHPS. The output power of each generation module in PHPS/Cavern is displayed in Figure 5. After the annual

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operating characteristics of the system being considered, the weekly output power of each power generation module was obtained by adding daily output in a week. In the cases analyzed in the present work, wind energy constituted the primary source of electricity generation. During periods with abundant wind resources, particularly in the spring, part of wind energy was used to electrolyze hydrogen and then stored. The stored hydrogen was transported to a gas turbine power plant, and there it was blended with natural gas to generate electricity during peak power periods such as winter. Wind modules and gas turbine generation contributed 65.63% and 33.9% of electrical load throughout the year, respectively.

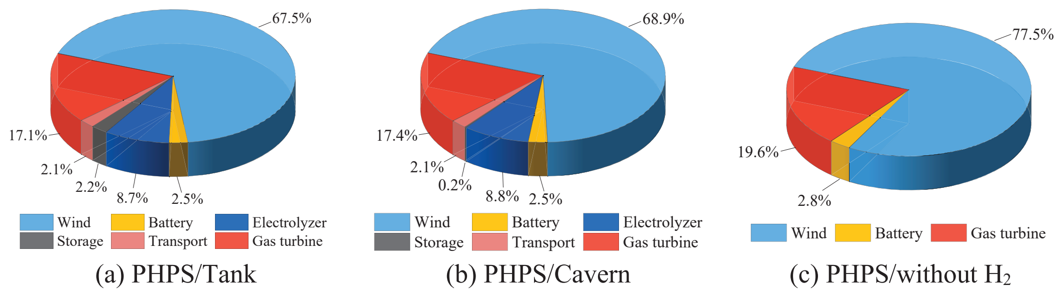

Figure 4: Proportion of investment in different equipment

In addition, electricity was stored by lithium-ion batteries when wind was redundant and released during peak periods. Batteries contributed 0.47% of the annual electricity generation, which was relatively small. The output power of the battery is depicted in Figure 6. Summer was the charging and discharging peak period of the batteries. It is vital to note that the utilization of batteries and gas turbines compensated to some extent for the volatility of wind power.

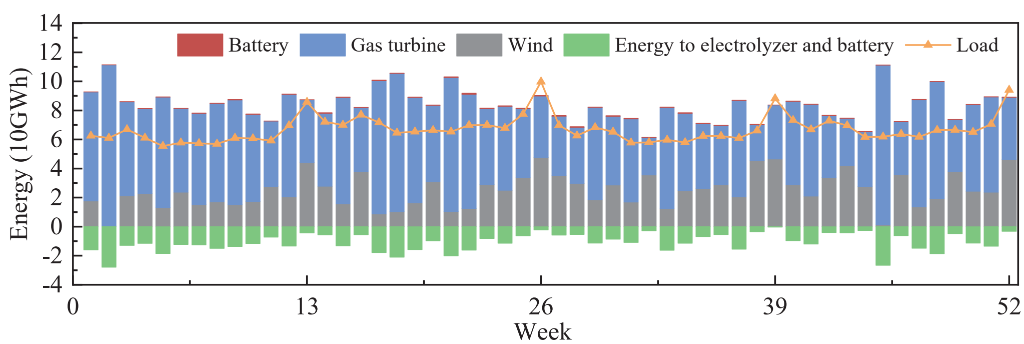

Figure 5: Output electricity of different equipment in PHPS/Cavern

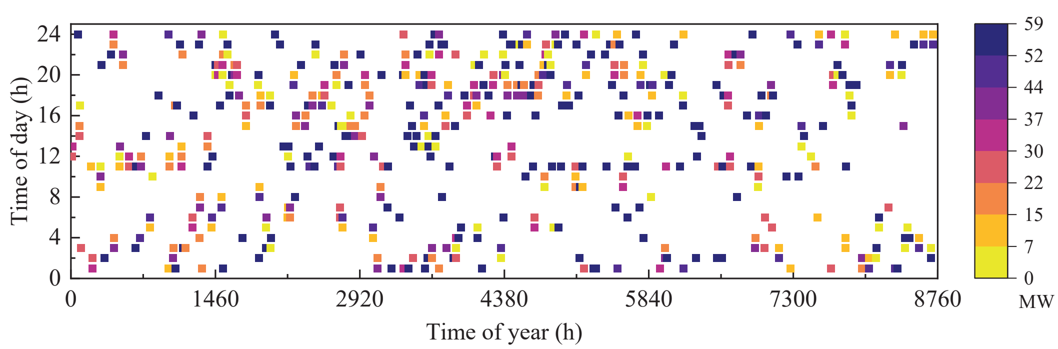

Figure 6: Output power of lithium-ion battery in PHPS/Cavern

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3.3 Influence of Different Hydrogen Substitution Ratios

The effect of different hydrogen substitution ratios on the system performance was investigated using PHPS/Cavern as a benchmark. Different hydrogen substitution ratios corresponded to various hydrogen demands, gas turbine operating characteristics, size of electrolyzer, and size of storage module. In the present work, five cases corresponding for different hydrogen substitution ratios ,0%, 10%, 20%, 30% (baseline), and 40%, were analyzed, on the basis of taking into account the limitations of the gas turbine on the hydrogen substitution ratio. The results obtained are displayed in Table 4. The economic competitiveness of the system decreased with increasing hydrogen substitution ratio. IRR, payback period, and LCOE of PHPS were 5.762%, 13.08 yr, and 0.051 €/kWh, respectively, when the hydrogen substitution ratio was 40%. The IRR of the PHPS with the hydrogen substitution ratio of 40% decreased by 10% compared to that of the baseline, while the payback period and LCOE increased by 16% and 3%, respectively. In addition, the renewable energy SE and CE of PHPS decreased with increasing hydrogen substitution ratio. The SE of the system with the 40% hydrogen substitution ratio was only 3.143% of system supply, which was 66% lower than that of the system with the 30% hydrogen substitution ratio and 85% lower than that of the system with the 0% hydrogen substitution ratio. When the hydrogen substitution ratio was 40%, the CE per kWh was 0.128 t/MWh, which was 6% lower than that in system with hydrogen substitution ratio of 30%. Thus, PHPS with higher hydrogen substitution ratios performed poorly economically but had significant advantages in terms of the increase in renewable energy utilization rate and emission reductions. The magnitude of change was more significant in the systems with higher hydrogen substitution ratio.

Table 4: Influence of different hydrogen substitution ratios

	0%	10%	20%	30%	40%
IRR (%)	7.255	7.058	6.771	6.410	5.762
Payback period (yr)	9.566	9.935	10.510	11.320	13.080
Net present value (10M€)	1.999	1.886	1.696	1.432	8.902
LCOE (€/kWh)	0.0480	0.0484	0.0491	0.0498	0.0515
SE (% system supply)	20.570	17.780	14.110	9.198	3.143
CE per MWh (t/MWh)	0.154	0.149	0.143	0.137	0.128

3.4 Parametric Analysis

Parametric analysis was carried out using PHPS/Cavern as the baseline scenario. Firstly, the investments of wind power module and electrolyzer module varied within the range of -20% to 20%. In addition, the transportation distance of hydrogen is a vital factor in the flexible scheduling of hydrogen resources. The LCOE and IRR of PHPS in hydrogen transportation distances of 0-600 km were investigated. Finally, the annual electricity revenue is a function of the electricity price. The sensitivity of the electricity price that varied from -5% to 5% was analyzed in the present work.

3.4.1 Influence of wind modules investment: As illustrated in Figure 7(a), wind modules investment exhibited a significant impact on the economics of the PHPS system, and the LCOE and IRR varied approximately linearly with the wind modules investment. The LCOE of PHPS decreased by 3% with a 10%-pts decrease in wind modules investment. In addition, the IRR of PHPS increased by 11.5% with a 10%-pts decrease in wind modules investment. This can be mainly attributed to the large initial investment share of wind modules. The economic advantage of onshore wind power in China was more significant compared to the one in the majority of countries in the world. The LCOE of onshore wind power in China was 0.022-0.032 €/kWh in 2022. Therefore, PHPS was economically viable in China. Furthermore, reducing the investment in wind modules is an important measure to improve the economics of PHPS.

3.4.2 Influence of electrolyzer investment: As depicted in Figure 7(b), the LCOE and IRR of PHPS exhibited only a slight dependence on fluctuations in electrolyzer investment. The LCOE of the PHPS decreased linearly with increasing electrolyzer investment, while the IRR increased linearly with increasing electrolyzer investment. With a 20%-pts decrease in electrolyzer investment, the LCOE of

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PHPS decreased by 1% and the IRR increased by 3%. Therefore, the performance of PHPS was almost independent of the electrolyzer investment.

3.4.3 Influence of transport distance: The LCOE and IRR of PHPS in different hydrogen transportation distances are presented in Figure 7(c). High-pressure gas hydrogen trailer transportation is commonly used for short-distance transportation. In addition, the system proposed in the present work integrated wind power modules, electrolyzer, and gas turbine, which required little flexibility in hydrogen transportation. Therefore, the system performance variation in the transportation distance of 0-600 km was investigated. The baseline distance was set at 300 km. The LCOE decreased by 1% and IRR increased by 3% when no transportation was required (0 km transportation distance) compared to those in the transportation distance of 300 km. Moreover, the LCOE of PHPS in the transportation distance of 600 km increased by only 0.1% compared to the one in transportation distance of 300 km. Therefore, the effect of transportation distance was almost negligible in the short distance of 0-600 km.

3.4.4 Influence of electricity price: The LCOE and IRR of PHPS at different electricity prices are displayed in Figure 7(d). The electricity prices considered in the present work were based on the hourly price with peaks and valleys in a typical day. In the sensitivity analysis of electricity prices, the hourly electricity prices were assumed to vary within the range of -5% to 5%. The LCOE of PHPS was independent of the electricity price. As depicted in Figure 8(d), the IRR of PHPS varied linearly with the variation in electricity price. With a 1%-pts increase in electricity price, IRR increased by about 3%. Therefore, the economics of the PHPS system was significantly dependent on the electricity price.

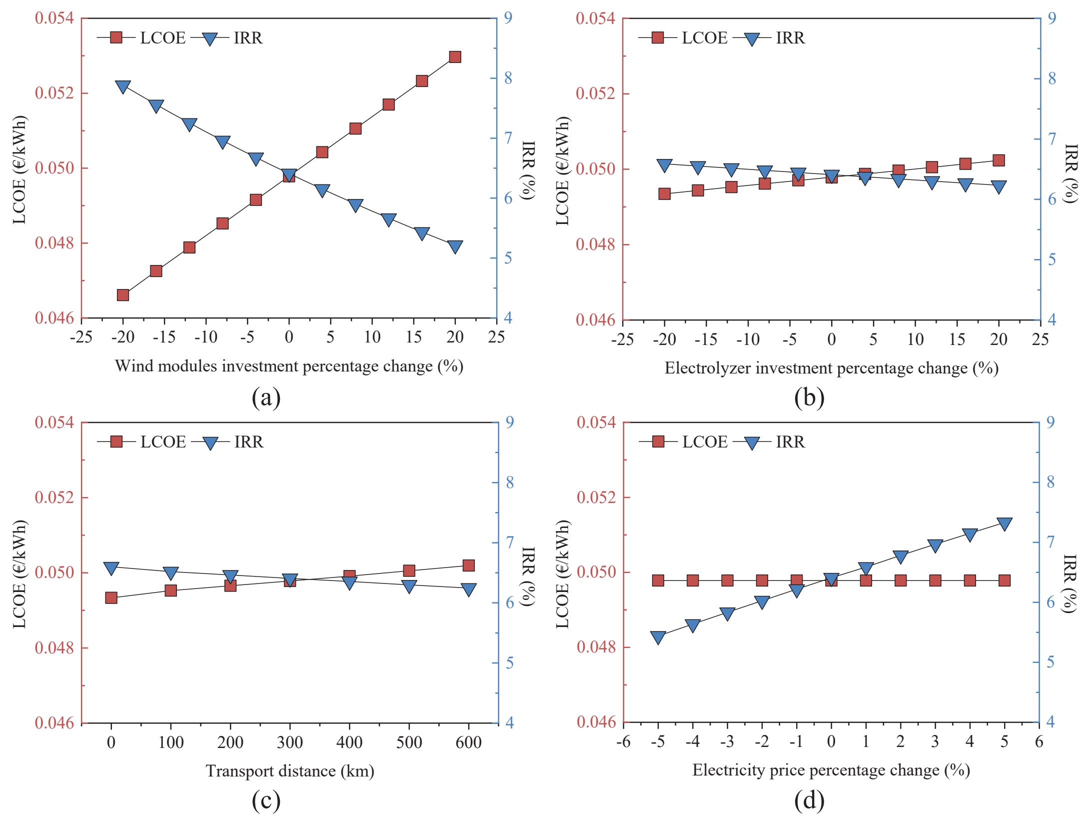

Figure 7: Influence of (a) Wind modules investment, (b) Electrolyzer, (c) Transport distance, and (d) Electricity price

3.5 Performance of PHPS under the Future Scenarios

In order to comprehensively and accurately evaluate the techno-economics of the PHPS system in

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Chinese future scenarios, the IRR, payback period, net present value, and LCOE of the PHPS in the period of 2030-2050 were investigated. The investments of wind modules, electrolyzer modules, battery modules, steel tanks, and salt caverns in the years 2030, 2040, and 2050 were selected according to the work of Abdin *et al*. (2022), Wang *et al*. (2023), Xu *et al*. (2023), Huang *et al*. (2023), Huang and Balcombe (2024), and Chen *et al*. (2024). In addition, other predictive data have been acquired, such as efficiency predictions of lithium-ion batteries (Tiede *et al*., 2022). The performance results of the PHPS system in 2030, 2040, and 2050 are given in Table 5. The installed cost of PHPS/Cavern decreased over time. The IRR of PHPS/Cavern would be 7.75%, 9.25%, and 10.43% in 2030, 2040 and 2050 respectively. The IRR of PHPS/Cavern would increase by 63% in 2050 compared with that in base scenario. In the base scenario, the IRR of PHPS/Tank and PHPS/Cavern was approximately 14% lower than that of PHPS/without H_2. However, in 2050, the IRR of PHPS/Tank and PHPS/Cavern can be merely 11% lower than that in PHPS/without H_2. Therefore, the substitutability of PHPS for fossil resources power generation system would gradually increase with the advancement of hydrogen-related technologies. The comparison results of the payback period of PHPS in future scenarios in China is summarized in Table 5. In 2050, the payback period of PHPS/Tank, PHPS/Cavern, and PHPS/without H_2 would be 5.89 yr, 5.80 yr, and 5.01 yr, respectively, which was equivalent to approximately 50% of that in base scenario. Furthermore, the LCOE of PHPS/Cavern would decrease by 6-15% with time.

Table 5: Performance comparison under the future scenarios

		Base	2030	2040	2050
IRR (%)	PHPS/Tank	6.217	7.620	9.131	10.321
	PHPS/Cavern	6.410	7.748	9.254	10.433
	PHPS/without H_2	7.255	8.624	10.333	11.594
Payback period (yr)	PHPS/Tank	11.800	8.950	6.980	5.890
	PHPS/Cavern	11.320	8.740	6.850	5.800
	PHPS/without H_2	9.566	7.546	5.879	5.012
Net present value (10^8€)	PHPS/Tank	1.275	2.320	3.223	3.815
	PHPS/Cavern	1.432	2.404	3.289	3.865
	PHPS/without H_2	1.999	2.839	3.681	4.188
LCOE (€/kWh)	PHPS/Tank	0.0502	0.0471	0.0444	0.0426
	PHPS/Cavern	0.0498	0.0469	0.0442	0.0425
	PHPS/without H_2	0.0480	0.0456	0.0430	0.0415

4 CONCLUSIONS

The power sector is a major generator of greenhouse gas emissions. Increasing the utilization rate of renewable resources is crucial for emission reductions in the power sector. However, renewable energy sources are fluctuating and intermittent, hence the level of renewable energy utilization needs to be improved. Hydrogen production using onshore wind power is an economically viable approach. Therefore, an integrated electro-hydrogen system coupling onshore wind power, electrolyzer, battery, and gas turbine was proposed. The techno-economic characteristics of PHPS were investigated. The conclusions were presented as follows:

1）The implementation of PHPS/Cavern can increase the utilization rate of wind power and realize systematic carbon emission reductions while maintaining the economic competitiveness of the system in the case of Shaanxi, China. The LCOE of PHPS/Cavern was 0.050 €/kWh, which was equivalent to 1.04 times that of PHPS/without H_2. However, SE and CE of PHPS/Cavern were 48% and 88% of those of PHPS/without H_2, respectively. Furthermore, the PHPS coupled with the cavern demonstrated greater economic competitiveness compared to the PHPS coupled with the tank.

2）Hydrogen substitute ratios and wind module investments significantly influenced the performance of the PHPS system. SE and CE could be reduced by 66% and 6%, respectively, when PHPS with a 30% hydrogen substitute ratio was redesigned to be the one with the hydrogen substitute ratio of

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40%. Nevertheless, PHPS with the hydrogen substitution ratio of 40% demonstrated lower economic competitiveness, resulting in an 10% reduction in IRR. In addition, with a 10%-pts decrease in the wind modules investment, the IRR of PHPS increased by 11.5%.

3） PHPS/Cavern emerged as a cost-competitive alternative to fossil resources power generation in 2050. In 2050, the IRR of the PHPS/Cavern can be increased to 10.32%, which was equivalent to 89% of that of PHPS/without H_2. Technological advances leading to cost reductions can substantially enhance the economic competitiveness of PHPS/Cavern. Therefore, there is an urgent need to accelerate the development of hydrogen-related technologies to realize large-scale green hydrogen power generation in power systems.

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