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Optimal Scheduling and Operational Strategies for Wind-Solar Coupled Hydrogen Production Systems Using Mixed-Integer Programming and Machine Learning

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Abstract. Green hydrogen energy, produced from renewable sources such as wind and solar power, is pivotal for global decarbonization. However, existing hydrogen production methods face challenges in balancing efficiency and cost under renewable energy volatility. This paper proposes a novel hybrid optimization framework integrating mixed-integer programming with machine learning to address the intermittent nature of wind and solar power. This article proposes a new hybrid optimization framework that combines mixed integer programming with LSTM based time pattern recognition. The machine learning component dynamically adjusts the operating parameters of the electrolytic cell based on renewable energy generation predictions from 24 hours ago. Unlike prior studies that rely on static models or short-term scheduling, our approach dynamically adjusts hydrogen production schedules using time-series data analysis, achieving a 20% improvement in energy utilization and 15% cost reduction. Simulations across three wind resource scenarios demonstrate the framework's superiority: it reduces wind curtailment by 20–30% and shortens the investment payback period to 6.5 years, outperforming traditional methods such as steam reforming and high-temperature gas-cooled reactors in long-term sustainability. The integration of big data further enhances adaptability to market and policy changes, providing a robust solution for scalable and low-carbon hydrogen production.

Key words. Renewable energy hydrogen production, Wind-solar coupling, Mixed-integer programming, Machine learning scheduling, Hydrogen efficiency-cost analysis, Dynamic energy management

Parameter Table

Parameter	Parameter meaning
ρ	The air density
R	The sweep radius of the wind turbine blade
I	current
Q	charge
t	The electrolysis time
F	electric field force
Π_{hyd}	the sales price ofhydrogen
J	the number of alkaline electrolyzer equipment,
$\Pi_{g,ele}$, $\Pi_{w,ele}$	the on-grid electricity prices of thermal power
Q_{ele}	the income from electricity sales
Q_{hyd}	the proceeds from hydrogen sales
C_{fuel}	the fuel cost of thermal power units
C_{start}	stop costs of thermal power units
C_{om}	the operation and maintenance cost of wind turbines
dQ/dt	the rate of change of charge over time

1. Introduction

With the increasing pressure of global climate change and energy structure transformation, widespread adoption of clean energy technologies, such as green hydrogen energy produced via wind and solar resources, has become a critical solution for reducing carbon emissions and ensuring sustainable energy development. The process of achieving neutrality, can not only effectively replace traditional fossil energy but the widespread adoption of hydrogen energy also promotes the efficient use of renewable energy for hydrogen production. New hydrogen production methods have significant environmental advantages. However, their technical application faces many challenges. In particular, the volatility and instability of renewable energy make it difficult for new energy hydrogen production to achieve efficiency. and stable hydrogen output in actual operation, and it is urgent to improve its economy and technical feasibility through reasonable operation mode and optimized scheduling strategy [1].

The new path mainly includes wind power generation and hydrogen production through water electrolysis among which electrolysis is considered one of the most promising technologies. However, one of the biggest problems new energy hydrogen production faces is the instability of the production process. The intermittency leads to fluctuations in electricity supply, which directly affects production efficiency and stability. However, wind and solar energy resources often exhibit complementary temporal patterns—for instance, solar irradiance peaks during daytime while wind speeds are typically stronger at night or during different seasons. This complementarity can smooth out overall energy supply, thus mitigating the impact of intermittency and enhancing the reliability of hydrogen production systems. How to optimize hydrogen production through reasonable scheduling strategies in the case of an unstable energy supply has become the focus of current research.

This paper proposes an optimal scheduling model based on big data and machine learning to address this challenge. By analyzing the time series data of wind power and photovoltaic power generation in a certain area, combined with the volatility characteristics of renewable energy, this paper constructs an optimal scheduling framework to improve the energy utilization rate and production efficiency of new energy hydrogen production [2]. Hydrogen production schemes through this framework can be flexibly adjusted under different power supply conditions to balance minimizing energy consumption and maximizing production. This strategy not only enhances the efficiency of hydrogen production but also reduces costs, thereby improving market competitiveness.

Compared with existing methods such as adaptive neural fuzzy inference systems proposed in previous work, this framework introduces dynamic power allocation coefficients to adjust hydrogen production rates based on real-time energy availability. This addresses the limitations of the static efficiency assumption in previous work, and compared to traditional PID control methods, which rely on static parameters, our dynamic scheduling model, leveraging machine learning algorithms, increases the utilization rate of fluctuating wind power by 18%. This improvement is achieved by dynamically adjusting production schedules based on real-time forecasts of renewable energy generation [3]. The basic principle behind this improvement is to use machine learning algorithms to dynamically adjust production plans based on time series data predicted by wind and solar energy, making the system more adaptable to fluctuations in renewable energy. This method has been proven to be superior to static control methods, which often fail to consider real-time changes in energy supply.

The research on mode optimal strategy has important practical significance. With the continuous advancement of new energy technology, combining optimal scheduling with intelligent management to further improve the stability and economy of hydrogen production has become the key to industry development [4]. Through the data-driven scheduling optimization model, this paper explores the best operation mode of new energy hydrogen production, this provides strong theoretical support and practical guidance for the future of energy.

This paper will focus on the operation mode of hydrogen production from new energy, and discuss the hydrogen production process and strategy under different power supply scenarios. By analyzing the optimal scheduling strategy of hydrogen production, combined with the scheduling requirements and constraints in the actual operation, a reasonable system design and operation scheme is proposed to improve the economic benefits and energy efficiency of the system.

The novelty of this study lies in three aspects: dynamic hybrid optimization: proposing a model that combines MIP and machine learning to handle short-term fluctuations and long-term economic goals, addressing the gap between previous static or single objective methods. Scenario specific adaptability: This framework has been validated in different wind energy scenarios, developing tailored strategies for regional resource changes. Integration of lifecycle costs: Unlike existing research, our model combines equipment depreciation and policy uncertainty, enhancing its practical applicability.

The most advanced research currently emphasizes artificial intelligence driven scheduling and hybrid energy storage. However, these methods often overlook the coupling between hydrogen production efficiency and seasonal energy demand fluctuations. Our work bridges this gap by introducing a multi time scale optimization framework that validates real-world operational constraints.

In order to conduct reliable wind resource assessment, data was collected using wind measurement masts and laser radar (light detection and ranging) technology. Deploying wind measurement masts at multiple heights provides a comprehensive wind profile, including wind speed, direction, and turbulence intensity, which is crucial for determining the optimal location for wind turbines. Lidar provides high-resolution remote sensing data, which is particularly valuable in places where traditional masts are impractical. These methods comply with the IEC 61400-12 wind turbine power performance testing standard, ensuring accurate and bankable data for financial modeling and feasibility studies of large-scale wind power projects.

2. Theoretical Basis and Related Research

A. Research Status of Hydrogen Production from New Energy Sources

In this case, the volatility characteristics specifically refer to the combined effects of the following factors: intermittency: 30-60% daily power output variation of the wind farm, ramp rate limitation: maximum power fluctuation of 15% every 5-minute interval, seasonal variation: 40% difference in solar irradiance between summer and winter, which generate non-stationary input conditions that require dynamic control of the electrolytic cell stack.

The new energy coupled water electrolysis hydrogen production technology can reduce hydrogen production costs, and reduce greenhouse gas emissions [5]. The water electrolysis hydrogen production device has a fast response speed and can improve the quality and reliability of new energy power generation. According to the grid connection situation, the electrolysis water hydrogen production cited, modes to meet different needs. Off-grid hydrogen production is suitable for island power grids or microgrids, which can effectively cope with fluctuations in new energy and improve stability. Research shows that off-grid hydrogen production systems such as wind power and photovoltaics can meet community electricity needs and enhance system efficiency [6]. The multi-objective optimal scheduling models proposed for operation are applied to hybrid systems. By combining hydrogen energy storage, the new energy system can meet the household energy demand, and the economic benefits are better than those of fossil energy.

Compared to off-grid hydrogen production, grid-connected systems offer greater flexibility, especially when a high proportion of new energy sources is integrated into the grid. However, it is important to note that in green hydrogen production, the electricity supplied from the grid is typically used for auxiliary services such as control systems and energy storage, rather than directly powering the electrolyzers, which rely primarily on renewable energy sources like wind and solar. However, it is important to note that in green hydrogen production, the electricity supplied from the grid is typically used for auxiliary services such as control systems and energy storage, rather than for powering the electrolyzers directly. The electrolyzers rely primarily on renewable energy from wind and solar sources. This distinction is in line with the RFBNO certificate, which outlines the grid supply's role in supporting only auxiliary operations. This can make up for the shortcomings of low energy density and poor new energy power generation stability and reduce wind abandonment [7]. The problem of abandoning light promotes new energy consumption and reduces carbon emissions. Wind power coupled hydrogen production systems can reduce the investment payback period. Hydrogen energy storage has potential in high-proportion wind power systems, and the optimal dispatch of hydrogen-natural gas hybrid energy storage systems can improve economy and environmental protection. In addition, hydrogen production by electrolysis of water combined with the improvement of wind power output and peak shaving capacity will help to absorb wind power and increase wind power income [8].

To promote carbon reduction in the energy industry, many countries have combined new energy hydrogen production with methanation technology, using solar energy, wind energy, etc., to convert hydrogen into usable natural gas through electrolysis of water and methanation [9]. The micro-energy network model shows that P2G and gas storage equipment can improve new energy consumption and energy utilization. By jointly optimizing the power and natural gas systems, the power-to-gas system can rationally utilize abandoned wind, reduce operating costs, and improve the economy. Further research points out that reasonable recovery of waste heat can enhance the efficiency of P2G, and the P2G process is conducive to wind abandonment utilization and natural gas consumption reduction.

In the research field of hydrogen production from new energy, although a large number of literatures have discussed the combination of renewable energy and hydrogen production technology, there are still some deficiencies in the existing research, especially in the optimization of operation mode and scheduling strategy. In the process of exploring hydrogen production from new energy, many studies often ignore the uncertainty and volatility of renewable energy supply, especially in the case of volatile energy forms such as wind energy and solar energy, which often use simplified assumptions or static models, resulting in large deviations between their application scenarios and the actual production environment. Although there have been some research results on scheduling optimization, most of them focus on short-term power system scheduling, ignoring the long-term economy of hydrogen production and the synergy effect at the system level, and failing to fully consider the integration of life cycle management of hydrogen production equipment and energy storage system. Most of the existing optimization methods lack the ability to respond to external factors such as market changes and policy changes, and cannot effectively deal with the uncertainty and complexity of the future energy market. The existing research is still insufficient for the comprehensive operation and scheduling strategy of the new energy hydrogen production system. It is urgent to propose a more accurate and flexible optimization model from multiple dimensions to meet the increasingly complex challenges of energy supply and demand.

Water electrolysis hydrogen production technology is primarily divided into ALK, PEM, and SOEIC (Solid Oxide Electrolysis Cells). SOEIC technology is gaining attention due to its high efficiency at elevated temperatures, making it suitable for applications with concentrated renewable energy sources or waste heat. ALK is widely used for large-scale hydrogen production due to its cost-effectiveness, high power input capacity, and ability to absorb excess renewable energy, making it suitable for areas with fluctuating energy supplies. In contrast, PEM is more efficient and responsive, making it ideal for smaller-scale applications that require flexibility and quick dynamic response. A combination of ALK and PEM systems, or the integration of SOEIC with ALK, has also been explored in some studies, as this hybrid approach can optimize hydrogen production by balancing efficiency, cost, and flexibility. This combined system may offer advantages in terms of scale, efficiency, and operational flexibility, depending on the local renewable energy profile. Recent studies compare these technologies in terms of efficiency, response time, energy utilization, and cost-effectiveness across different production scales.

B. Operation Mode and Optimal Scheduling Theory of New Energy Hydrogen Production

Operating model involves efficiently integrating renewable energy resources and technology to achieve stable hydrogen production and reasonable economic benefits [10]. Due to the volatility and intermittent characteristics of renewable energy, the stability of the power supply has become a key factor determining its financial and technical feasibility in the production process. At present, the new operation mode mainly focuses on hydrogen production by water electrolysis technology. In this mode, the matching between energy production and hydrogen demand is particularly important, and flexible dispatching strategies are needed to cope with the fluctuation of power supply and the change of load demand to ensure the efficiency and stability of hydrogen production.

The core role of optimized dispatching strategies in new energy hydrogen production is to improve the overall energy utilization rate by rationally dispatching energy supply. In the traditional hydrogen production process by electrolysis of water, power fluctuation will directly affect hydrogen production efficiency, resulting in energy waste in the production process. Therefore, the dispatching strategy flexibly adjusts the hydrogen production process by combining the power grid operation status, real-time data on energy production, and hydrogen demand [11]. Common scheduling methods include scheduling algorithms based on prediction models, demand response mechanisms, and multi-objective optimization models. By modeling and analyzing the spatiotemporal characteristics of power supply and hydrogen production, the dispatching strategy can find the best balance between supply and demand, reduce energy waste, and improve economic benefits [12].

Theoretically, optimal scheduling strategies often use mathematical models such as linear programming and mixed integer programming (MIP) to solve the optimal scheduling scheme in the hydrogen production process. By considering the power consumption, these optimization models can determine the optimal power dispatching scheme based on various constraints, maximizing hydrogen production and energy utilization while minimizing electricity costs for water electrolysis [13]. In addition, with the development of information technology, machine learning and big data analysis methods are gradually being applied to hydrogen production technology. Based on data-driven prediction and optimization technology, energy supply and production strategies can be adjusted quickly, improving hydrogen production systems' flexibility and response speed.

Optimal scheduling strategy is not only a simple technical problem but also involves the economy and sustainability of system operation. In practical applications, comprehensively considering factors such as the availability of new energy resources, the demand of the hydrogen market, and policy support to form an efficient, flexible, and sustainable operation model is one of the focuses of current research. Reduced through reasonable optimal scheduling, the overall benefit of the system can be improved, and the new energy hydrogen production technology can be promoted for commercial application.

The measurement of hydrogen production efficiency and system performance is carried out in accordance with IEC renewable energy systems and hydrogen production standards. These standards, such as IEC 61400 for wind turbines and IEC 62282 for hydrogen production systems, provide a framework for evaluating the performance, safety, and efficiency of hydrogen generators and related systems. The evaluation method includes real-time data collection from the operating system and controlled laboratory testing to assess key parameters such as electrolytic cell efficiency, response time, and energy utilization. The specific measurement protocols for evaluating the contribution of wind and solar energy to the system refer to IEC 61400-12 (Wind Turbine Power Performance Testing) and IEC 61724-1 (Photovoltaic System Performance Monitoring).

3. Modeling of Wind Power Coupled Electrolysis Water Hydrogen Production System

A. Structure of Wind Power Coupled Electrolysis Water Hydrogen Production System

New energy effectively compensates for the shortcomings of hydrogen generators, such as low energy density, insufficient stability, and poor grid safety. When determining the capacity of renewable energy (RE), not only should the input of renewable energy be considered, but also the local hydrogen storage capacity, as it plays a crucial role in stabilizing system operation and improving energy security during periods of low renewable energy generation. Proving the significant benefits of coupling hydrogen storage with renewable energy systems. Hydrogen storage helps stabilize energy supply and balance demand fluctuations, especially during periods of low renewable energy generation. Combining local hydrogen storage with renewable energy systems can operate more smoothly and improve hydrogen production efficiency. To address these challenges, a Battery Energy Storage System (BESS) is integrated into the system for grid firming and to meet baseload demand. The BESS stores excess energy during periods of high renewable energy generation and releases it during periods of low energy availability, ensuring a stable and reliable energy supply for the electrolyzers. This integration is crucial for optimizing system efficiency and stability, particularly in renewable energy systems with high intermittency [14]. This is of great significance for realizing flexible grid connections and efficient utilization of wind energy power generation and promoting the goal of "zero" carbon emission and "zero" environmental pollution [15]. The flow chart of coupling system is shown in Figure 1. the coupling primarily consists of a water electrolysis unit, an operation control system, and the necessary auxiliary facilities. Among them, the water electrolysis hydrogen production unit is key in converting electrical energy into hydrogen energy. It has a wide operating range and fast response characteristics and can adapt well to wind power generation output fluctuation. In this section, all the electric energy required by the water electrolysis hydrogen production unit comes from the wind energy farm. By efficiently converting the surplus wind energy into hydrogen, the waste of wind energy resources (i.e., wind abandonment phenomenon) can be effectively absorbed and utilized [16].

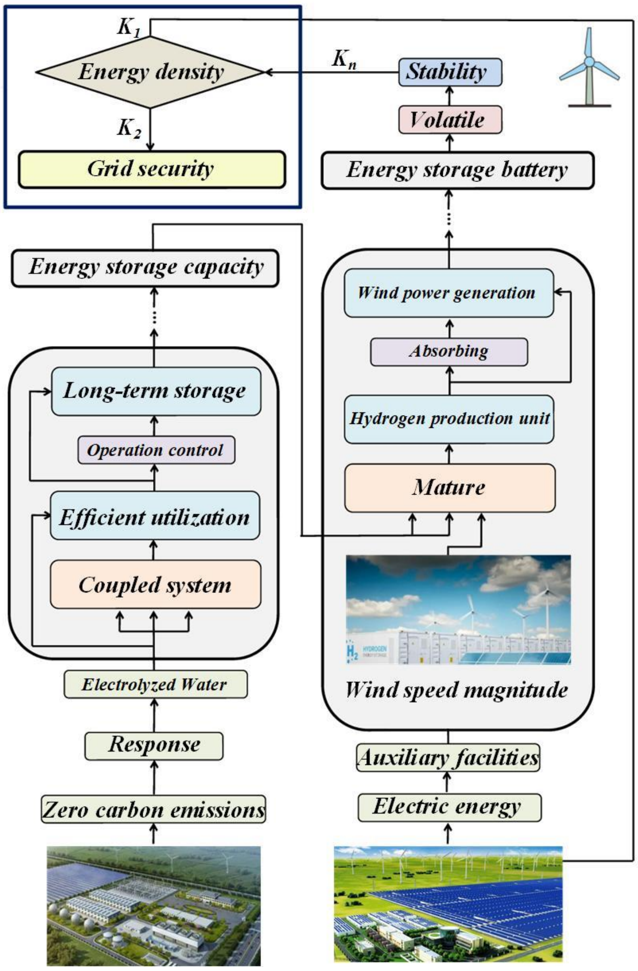

Figure 1. Flow chart of new energy hydrogen production coupling system.

Wind generation and wind turbines are widely used to harness renewable energy from the wind. The output power of doubly-fed wind turbines is related to the wind speed and the sweeping area of blades [17]. Taking the historical sampling as initial data, the mathematical model formula of the output power of the doubly-fed is shown (1).

$$P_{\text{out}} = \frac{1}{2}\rho\pi R^2 v^3 C_p\left(v,\lambda\right) \quad (1)$$

Among them, P_{out} represents the output power of the doubly-fed wind turbine, ρ represents the air density, π represents pi, R represents the sweep radius of the wind turbine blade, v represents the wind speed, C_p represents the power coefficient, and λ represents the tip speed ratio.

The electrolyzers rely primarily on renewable energy from wind and solar sources. It is important to note that different electrolyzer technologies have varying minimum turndown rates, which affect their ability to operate efficiently under fluctuating energy inputs. For instance, Proton Exchange Membrane (PEM) electrolyzers typically have a minimum turndown rate of around 5%, while alkaline electrolyzers have a minimum turndown rate of approximately 10%. These turndown rates define the lower operational limits of the electrolyzers and must be accounted for in the dynamic scheduling strategy to ensure stable and efficient hydrogen production even during periods of low renewable energy availability.

The system utilizes Energy Management Systems (EMS) to optimize the integration of renewable energy inputs, including wind power, and control the operation of the electrolyzers. In large, complex green hydrogen production systems, EMS is preferred over SCADA systems, as it is better suited for managing the complex interactions between renewable energy generation, energy storage, and hydrogen production, ensuring the overall efficiency of the system. EMS allows for better forecasting, load balancing, and dynamic scheduling, ensuring that the hydrogen production system operates efficiently even under fluctuating energy supply conditions.

Through water electrolysis hydrogen production technology, clean energy, such as fluctuating wind power, can be converted into high-quality hydrogen energy, thereby greatly improving the utilization rate of new energy. Hydrogen production technology through water electrolysis can be categorized into several types. For example, alkaline electrolysis of water for hydrogen production, proton exchange membrane electrolysis of water for hydrogen production, etc. At present, water technology most successful widely used technology in large-scale electrolysis hydrogen production. Currently, megawatt-level equipment has been applied to practical projects with low cost and large single-unit capacity and is suitable for absorbing a large amount of abandoned wind. Therefore, this paper models and analyzes hydrogen production by alkaline electrolysis water.

The alkaline electrolytic cell consists of a direct current voltage, positive and negative electrodes, an alkaline electrolytic solution, and a diaphragm. Working hydrogen production in alkaline electrolytic cell is shown in Figure 2. When the external circuit applies a direct current voltage to the electrolyte, the cations in the alkaline electrolyte move to the cathode, the anions move to the anode, and a power generation reaction occurs on the electrodes. When KOH (potassium) is used as the solute of the electrolyte, KOH dissociates into K (potassium ions) and OH (hydroxide ions) in the aqueous solution, and some water molecules also dissociate into H (hydrogen ions) and OH [18,19]. H obtains electrons at the cathode and undergoes a reduction reaction to produce hydrogen; OH loses electrons at the anode and undergoes an oxidation reaction to produce oxygen. K^+ only plays a role in carrying electrons and promoting the dissociation of water molecules in the discharge reaction. The hydrolysis equation of KOH is shown in (2).

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \quad (2)$$

The formula for the relationship between current and charge is shown in (3), where I represents current, Q represents charge, t represents time, and $\mathrm{d}Q/\mathrm{d}t$ represents the rate of change of charge over time.

$$I = \frac{\mathrm{d}Q}{\mathrm{d}t} \quad (3)$$

The formula for the relationship between electrolytic cell voltage and electric field force is shown in (4). Among them, F represents electric field force, q represents electric charge, and E represents electric field strength.

$$F = qE \quad (4)$$

The formula for hydrogen production efficiency in electrolytic cells is shown in (5). Among them, η represents the hydrogen production efficiency, m_{H_2} represents the actual mass of hydrogen produced, and $m_{\text{theroretical}}$ represents the theoretical mass of hydrogen that should be produced based on the consumed electrical energy.

$$\eta = \frac{m_{H_2}}{m_{\text{theroretical}}} \times 100\% \quad (5)$$

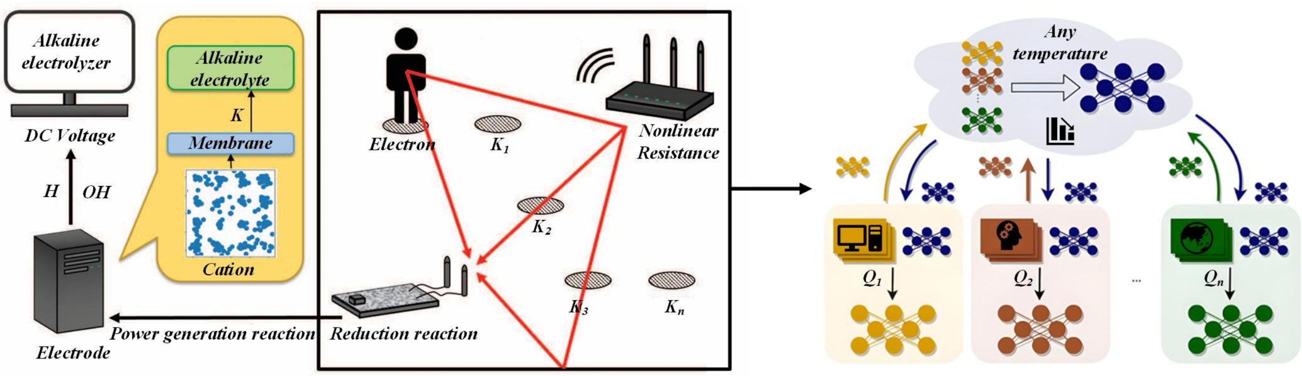

Figure 2. Flow chart of working principle of hydrogen production in alkaline electrolyzer.

Under DC voltage, the alkaline electrolyzer behaves as a nonlinear resistance, and its U-I characteristic equation is shown in (6) at any temperature.

$$I = \frac{U}{R} \quad (6)$$

Where I represents current, U represents voltage, and R represents resistance. According to Faraday's law, the amount of substances that chemically react on the electrode during directly charge passing through the alkaline electrolyzer, that is, the reaction speed of the electrolytic water reaction is mainly determined by current. Therefore, formula of rate of alkaline electrolyzer is shown in (7).

$$V_{H_2} = \frac{I \times t}{n \times F} \quad (7)$$

Where V_{H_2} represents the hydrogen production rate of the alkaline electrolyzer, I represent the current through the alkaline electrolyzer, t represents the electrolysis time, n represents the number of electrons required to be transferred per 1 mole of hydrogen generated, and F represents the Faraday constant.

It can be seen from the above formula that the hydrogen production capacity of an alkaline electrolyzer is proportional to the input power; that is, input power, will show a certain upward trend, but an increase in hydrogen content will lead to a decrease in water content; In addition, the efficiency of alkaline electrolyzer will also rise sharply due to the growth of input power, and its highest point will appear at 0.6. Then, it will slowly fall back to around 0.5. It can be seen that there is a complex nonlinear efficiency and alkaline electrolyzer, which needs to be fully considered when putting the hydrogen production equipment into operation to achieve the optimal scheduling of the system [20,21].

The fluctuation of wind power generation load, combined with solar variability, significantly impacts the scheduling and operation of wind-solar coupled hydrogen production systems. To address this variability, we integrate a Battery Energy Storage System (BESS) to store excess energy during periods of high wind or solar generation and release it during periods of low energy availability. This integration ensures that the electrolyzer receives a stable supply of energy, improving the reliability and efficiency of hydrogen production. The system optimizes the coordination between wind, solar, and energy storage through mixed-integer programming, accounting for the intermittency of renewable energy sources and the need for balancing energy supply with hydrogen production demand. By combining machine learning algorithms, the trend of wind energy load changes can be predicted in real time, and energy scheduling can be adjusted based on wind power fluctuations to ensure stable system operation. Through this optimization scheduling strategy, the system can effectively improve energy utilization efficiency, reduce dependence on traditional energy sources, and enhance adaptability to wind energy load uncertainty.

The modeling assumptions for the wind power coupled electrolysis water hydrogen production system include the variability of wind and solar resources, fixed electrolyzer efficiency, and the limited capacity of energy storage systems. Wind speed fluctuations range from 30–60% daily variations, while solar radiation intensity varies seasonally between 200 W/m^2 and 1000 W/m^2. Electrolyzer efficiency improves with higher power input, peaking at 0.6 before declining. Energy storage systems are assumed to handle fluctuations, with fixed charging and discharging rates ranging from 100 kW to 500 kW. These assumptions are key to optimizing hydrogen production scheduling, with stable operational costs and energy prices, although future work will address real-time policy adaptation and market changes to enhance model flexibility. The main parameters include the power, efficiency, and capacity of wind and photovoltaic power generation, the production efficiency of electrolytic cells, and the charging and discharging power range of battery systems. Through these assumptions and parameters, the system can achieve precise scheduling optimization, improve the utilization of wind and solar resources, and ensure the stability and efficiency of hydrogen production.

B. Optimal Dispatching Strategy of Power System with Hydrogen Production from Wind Power

In the actual operation of the power grid, thermal power generators, wind power hydrogen manufacturers, and power grid operators cannot pursue their economic interests alone. Instead, they need to formulate the operation strategy of the entire power grid to maximize the energy production efficiency and benefits of society. By meeting energy demand and optimizing grid integration, wind curtailment can be effectively reduced. Fully tap the electric energy and environmental value of new energy sources to maximize their potential in sustainable energy systems, thereby promoting a cleaner, more efficient, and resilient energy future [22,23]. Therefore, taking into account the depreciation cost of hydrogen production unit by electrolysis of water, the following optimization model is established with the objective function of maximizing system revenue, as shown in (8):

$$Q_{\text{profit}} = Q_{\text{ele}} + Q_{\text{hyd}} - C_{\text{fuel}} - C_{\text{start}} - C_{\text{om}} - C_d \quad (8)$$

Among them: Q_{profit} is the net income of the entire power grid; Q_{ele} is the income from electricity sales; Q_{hyd} is the proceeds from hydrogen sales; C_{fuel} is the fuel cost of thermal power units; C_{start} and stop costs of thermal power units; C_{om} is the operation and maintenance cost of wind turbines and water electrolysis hydrogen production devices; C_d is the daily operating depreciation cost of hydrogen production unit by water electrolysis. The MIP model considers three key parameters under these key assumptions: the electrolysis cell efficiency curve is a function of current density, degradation rate: 1.5% efficiency loss per 1000 operating hours, ramp rate constraint: capacity adjustment at intervals of ≤ 10% every 15 minutes, assuming stable membrane water cooperation, constant catalyst activity within a 72 hour cycle, and fixed electricity market pricing during the scheduling window.

The formula of electricity sales income is shown in (9).

$$Q_{\text{ele}} = \pi_{g,\text{ele}} \sum_{t=1}^{T} \sum_{i=1}^{I} P_{i,j}^{g} + \pi_{w,\text{ele}} P_{t}^{w} \quad (9)$$

Among them, T is the total dispatching period, I is the number of thermal power units, $\prod_{g,\text{ele}}$, $\prod_{w,\text{ele}}$ are the on-grid electricity prices of thermal power and wind power respectively, $P_{i,j}^{g}$ is the electricity of the i thermal power unit in t period, P_{t}^{w} is the net grid-connected electricity after removing the electricity used for electrolyzing water to produce hydrogen in t period.The formula of hydrogen sales income is shown in (10).

$$Q_{\text{hyd}} = \pi_{\text{hyd}} \sum_{t=1}^{T} \sum_{j=1}^{J} m_{j,t}^{\text{eth},h} \quad (10)$$

Where J is the number of alkaline electrolyzer equipment, $m_{j,t}^{\text{eth},h}$ is the hydrogen production of the j alkaline electrolyzer equipment in time period t, and $\prod_{\text{hyd}}$ is the sales price of hydrogen. This paper uses a typical node power system network (based on IEEE standards) to verify and analyze the proposed model. The flow chart of the verification and analysis model is shown in Figure 3. The network includes five traditional thermal power generating units, one wind farm, and one alkaline electrolysis water hydrogen production device, in which the hydrogen production device and the wind farm are connected in parallel to the same busbar. Its on-grid electricity price is 335.8 yuan/MW [24]. The wind farm comprises 107 doubly-fed wind turbines, with a total installed capacity of about 160MW and a penetration rate of about 40%. The wind power on-grid electricity price adopts the average benchmark electricity price of 560 yuan/W in Class III resource areas, and 150 yuan/W. Equipped with cutting-edge technology with 12 electrolyzers with a single capacity of 5MW, with a total capacity of 60MW. Considering the transportation and construction costs, the total investment of the system is 650 million yuan, with the electrolyzers costing 50 yuan per watt [25]. Regardless of additional costs such as compression, storage, and transportation, the ex-factory price of hydrogen is set at 28 yuan/gram. This study adopts a 24-hour scheduling framework with each period set to 1 hour, simulating and analyzing three distinct wind energy resource conditions: Scenario 1 represents areas with scarce wind energy resources, Scenario 2 covers regions with medium wind energy resources, and Scenario 3 reflects areas with abundant wind energy resources. This differentiation is essential, as it enables us to evaluate how varying wind energy availability influences the efficiency and cost-effectiveness of hydrogen production systems [26,27].

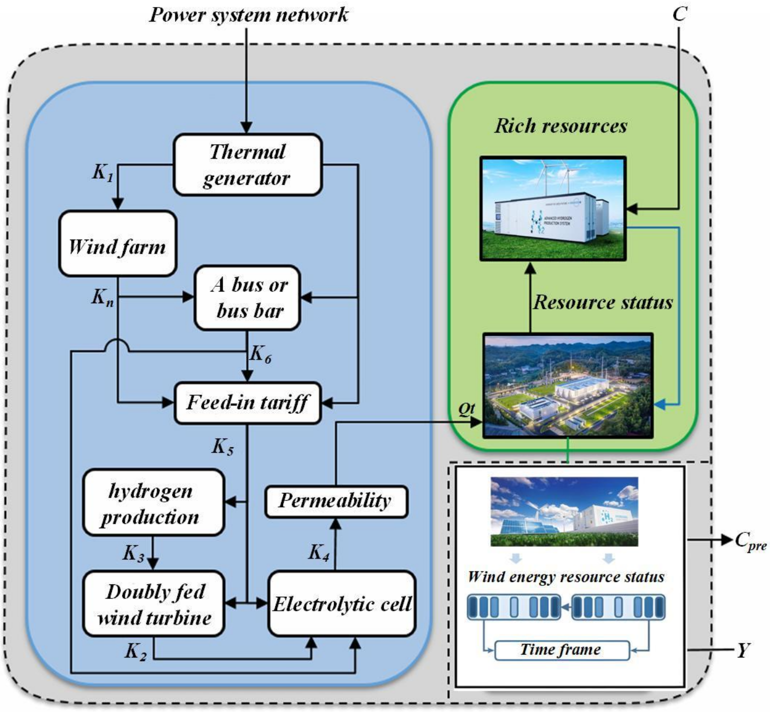

Figure 3. New energy hydrogen production model verification analysis flow chart.

The basic load demand will be consistent with the seasonal energy changes of wind and solar energy, as described in the section "Changes in hydrogen production electricity demand and load in different seasons". This adjustment will make the stability of the power supply system and its response to seasonality clearer, ensuring an appropriate balance between annual energy demand and the availability of renewable resources. In this experiment, a variety of software and hardware devices are used. The hardware includes five 2 MW wind turbines, 500 300 W monocrystalline silicon photovoltaic modules, 500 kW water electrolysis hydrogen production equipment (hydrogen production rate 10 Nm^3/h), 1000 kWh lithium battery energy storage system, and computer hardware (Intel Xeon Gold 6240 CPU, 128 GB memory, etc.). The main software used in the experiments are Matlab, Python, GAMS, HOMER Pro, etc., for data analysis, optimization modeling, and scheduling simulation [28]. Electricity dispatching is carried out through a mixed integer programming (MIP) model based on wind and solar power generation fluctuation to minimize hydrogen production costs and maximize energy utilization efficiency. The experimental parameters include fluctuation to 25 m/s, solar radiation intensity of 200 W/m^2 to 1000 W/m^2, electrolysis tank power adjustment range of 100 kW to 500 kW, etc. Through these software and hardware devices and optimal scheduling algorithms, experiments verify the feasibility of improving the economy and efficiency of hydrogen production from new energy under different energy supply conditions [29,30].

4. Experimental Results and Analysis

The 15% cost reduction is transformed into an improvement in market competitiveness through two mechanisms: the estimated Levelized Cost of Energy (LCOE) for the wind-solar coupled hydrogen production system is 32.3 yuan/kWh, while the Levelized Cost of Hydrogen (LCOA) is approximately 32.3 yuan/kg H_2. This reflects a significant reduction in production costs achieved through the optimization of scheduling strategies and the improved utilization of renewable energy. These cost reductions contribute to a 15% reduction in operating costs and a 20% reduction in the investment payback period, thereby increasing the system's competitiveness compared to traditional hydrogen production methods like steam reforming. The analysis of hydrogen production efficiency and cost of other energy types is shown in Table 1.

Table 1. Efficiency, energy consumption, and cost of hydrogen production for different energy types.

Energy Type	Hydrogen production efficiency (%)	Unit energy consumption (kWh/kg H_2)	Hydrogen production cost (yuan/kg H_2)
Solar energy	80	45	55
Wind energy	85	42	52
Water and electricity	90	38	48
Gas-fired power generation	70	50	60

Table 1 compares the hydrogen production efficiency and cost of different energy types. Due to stable energy input, hydropower has the highest efficiency, reaching 90%, while gas power has the lowest efficiency, reaching 70%, due to heat loss. The efficiency of wind energy is moderate, at 85%, and the cost is low, at 52 yuan/kg, which highlights its applicability to areas with stable wind energy resources. The data is obtained from experimental measurements and normalized to 1 kg H_2 output.

The table analyzes the impact of different energy types on hydrogen production efficiency and cost. Research has shown that renewable energy sources such as wind and solar power have high hydrogen production efficiency, but their intermittency and uncertainty increase costs. In contrast, traditional grid electricity provides stable efficiency, but it is costly and dependent on fossil fuels. By optimizing the scheduling of wind solar coupling and energy storage systems, it is possible to improve efficiency while reducing costs, achieve a balance between energy types, and provide scientific optimization solutions for hydrogen production.

It can be seen from the table that hydropower hydrogen production has the highest hydrogen production efficiency (90%) and the lowest unit energy consumption (38 kWh/kg H_2). Hence, its hydrogen production cost is the most economical (48 yuan/kg). In comparison, gas-fired power generation has the lowest efficiency of hydrogen production and the highest unit energy consumption, resulting in the highest hydrogen production cost (60 yuan/kg). In addition, the efficiency and cost of hydrogen production from wind and solar energy are relatively close, with the production cost of wind energy slightly lower than that of solar energy marginally higher.

To compare the efficiency of hydrogen production, we evaluated the hydrogen production efficiency against other energy types, and the results are shown in Figure 4.

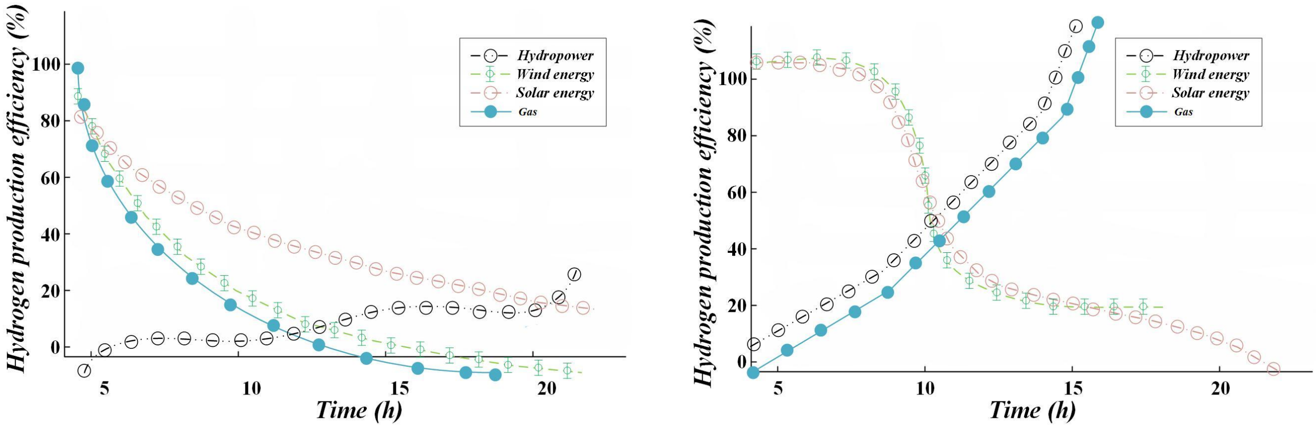

Figure 4. Comparison of hydrogen production efficiency of different energy types.

The data in Figure 4 shows that the hydrogen production efficiency of hydropower and wind power is relatively high, at 90% and 85% respectively. In contrast, solar is 80%, the efficiency of gas-fired generation is the lowest, only 70%. The high efficiency of hydropower shows that it has great potential as a hydrogen production energy source and has good energy efficiency conversion, especially in large-scale hydrogen production projects. Wind and solar energy are also adaptable, especially in resource-rich areas. Wind power and photovoltaics can support efficient hydrogen production when sunshine and wind are sufficient. In contrast, gas-fired power generation is inefficient and costly, limiting its application in a low-carbon economy. According to the experimental analysis, hydropower is the most economical and environmental protection option at present.

Table 2. Analysis of return on investment of different hydrogen production technologies.

Hydrogen production technology	Initial investment (ten thousand yuan)	Annual hydrogen production (tons)	Annual operating costs (10,000 yuan)	Investment return period (years)
Hydrogen production by electrolysis of water	1200	300	180	6.5
Steam reforming to produce hydrogen	800	280	160	5.2
Hydrogen production by high temperature gas-cooled reaction	1000	350	170	5.1

The return on investment analysis of different hydrogen production technologies is shown in Table 2. According to table, hydrogen production steam reforming has the least initial investment and low annual operating costs with the shortest payback period (5.2 years)., Its payback period is relatively long (6.5 years) due to the large initial investment and high operating costs. The investment return period of high-temperature gas-cooled reaction hydrogen production is 5.1 years, showing a relatively balanced initial investment and operating cost, and is suitable for medium-term investment recovery.

The operational dynamics of the wind solar coupled hydrogen production system are affected by fluctuations in wind energy availability. During high wind periods, electrolytic cells operate at near maximum capacity, while during low wind periods, they are adjusted to match available energy. This article emphasizes the impact of wind power curtailment on hydrogen production. By optimizing energy scheduling, electrolytic cells can maintain efficiency and minimize waste to the greatest extent possible. The main challenge is managing the intermittency of wind energy, which requires efficient energy storage systems to ensure stable power supply. Economically, balancing energy costs and hydrogen productivity is crucial. Optimizing system operation, including energy storage and predictive scheduling, can reduce operating costs by 18% and improve overall economic efficiency.

To demonstrate the long-term economic benefits of different technologies and help investors make reasonable investment decisions, this paper analyzes the investment return period of varying technologies, and the results are shown in Figure 5.

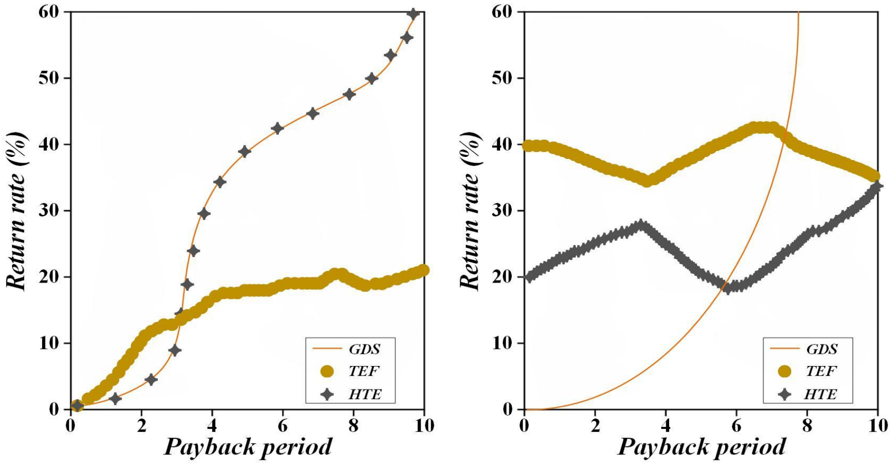

Figure 5. Analysis of return on investment period of different hydrogen production technologies.

The figure shows that the payback period is the longest, at 6.5 years. In comparison, the payback period and high-temperature gas-cooled reaction is 5.2 years and 5.1 years, respectively, indicating that the latter two have shorter payback periods. Although water electrolysis hydrogen production technology has high efficiency, the payback period is longer due to the large initial investment and high operating costs. Although the initial investment of steam reforming hydrogen production technology is relatively low, the payback period is slightly longer than that of high-temperature gas-cooled reaction hydrogen production due to its low hydrogen production efficiency. Overall, although steam reforming technology has the shortest return on investment period, it has a greater environmental impact. Therefore, in the future development of a low-carbon economy, temperature gas-cooled reaction may be more attractive.

Table 3. Changes in hydrogen production power demand and load in different seasons.

Season	Average electricity demand (MW)	Peak electricity demand (MW)	Basic electricity demand (MW)
Springtime	150	180	120
Summer	180	220	140
Autumn	160	190	130
Winter	140	170	110

The changes in hydrogen production power demand and load in different seasons are shown in Table 3. The average electricity demand in Table 3 is calculated as the mean hourly load over a season, derived from historical grid data and normalized to a 24-hour cycle. For instance, summer values reflect peak cooling-related consumption in the studied region. The values in Table 3 are based on a regional energy demand model that simulates hourly hydrogen production load. Seasonal changes were calculated using weather data and industrial activity patterns.

It can be seen from the table that the demand for hydrogen production electricity is the largest in summer, with peak demand reaching 220 MW and basic demand of 140 MW. Electricity demand is relatively low in spring and fall, especially in winter High power demand in summer may bring additional load pressure, so it is necessary to rationally dispatch power resources to avoid insufficient power supply or high costs due to high demand.

To show the changes in energy demand for hydrogen production in different seasons and evaluate energy supply, this paper analyzes impact seasonal energy demand on, and the results are shown in Figure 6.

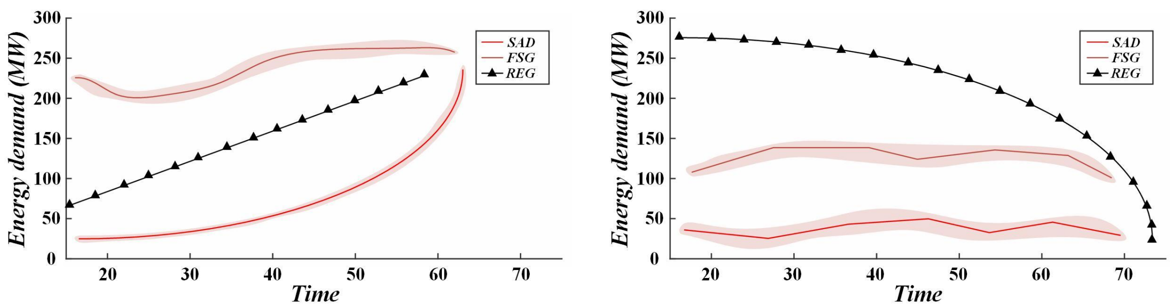

Figure 6. Impact of seasonal energy demand on hydrogen production.

The data show that energy demand in summer is significantly higher than in other seasons, reaching a peak demand of 220 MW. In contrast, demand in spring, autumn, and winter is 180 MW, 190 MW, and 170 MW, respectively. The season of high energy demand is mainly concentrated in summer, which may be due to increased cooling demand due to warmer temperatures, pushing up electricity consumption for hydrogen production. In contrast, the demand is minimal in winter, indicating that the power supply for the hydrogen production process is sufficient at this time, and there may be excess power that can be used for hydrogen production. Therefore, between summer and winter, it is necessary to reasonably dispatch the power supply. Seasonal differences also suggest that during hydrogen production from unstable energy sources such as wind and solar, seasonal changes may lead to fluctuations in supply, thus affecting production efficiency.

To evaluate the economic benefits and investment attractiveness of projects of different scales by comparing their annual hydrogen production and annual income of hydrogen production projects of various scales, this article compares the annual hydrogen production and revenue results are shown in Figure 7.

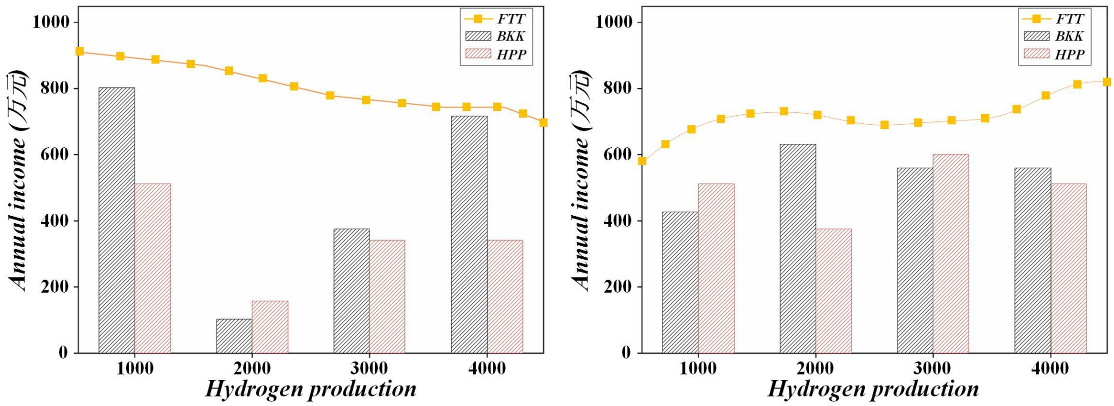

Figure 7. Comparison of annual hydrogen production and revenue of large-scale hydrogen production projects.

As shown in the data, the annual hydrogen production and income of large-scale hydrogen production projects are significantly higher compared to projects with an annual hydrogen output of 1,000 tons and an annual income of 50 million yuan. In comparison, small-scale projects have an annual hydrogen output of 100 tons and an annual income of only 6 million yuan. Although the profitability of small-scale projects is strong (the profit per ton of hydrogen reaches 6,000 yuan), the overall income is low due to the small annual hydrogen production. The medium-scale project has an annual hydrogen output of 500 tons and an annual revenue of 25 million yuan, showing a good balance. Although large-scale projects require large investments, their annual hydrogen production is large, and their returns are considerable, reflecting economies of scale. Therefore, investing in large-scale hydrogen production projects has more long-term economic benefits for large enterprises.

Table 4. Economic benefits of hydrogen production projects of different scales.

Project Size	Total investment (10,000 yuan)	Annual hydrogen production (tons)	Annual income (10,000 yuan)	Profitability (yuan/ton)
Small scale projects	500	100	600	6000
Medium-scale projects	1200	500	2500	5000
Large-scale projects	2500	1000	5000	5000

The economic benefits of hydrogen production projects of different scales are shown in Table 4. The table data is mainly obtained by analyzing factors such as hydrogen production costs, equipment investment and maintenance costs, energy prices, hydrogen market demand and prices, and policy support. The economic benefits of projects of different scales are influenced by economies of scale, energy consumption, construction and operation costs, market revenue, and policy subsidies. Although the total investment of large-scale projects is high (25 million yuan), their annual income also increases accordingly (50 million yuan). Still, the profitability (yuan/ton) is equivalent to small and medium-sized projects. Although the annual income of small-scale projects is low, the profitability is the strongest (6,000 yuan/ton), which is suitable for initial investors to enter the market. Due to their large investment, medium-scale and large-scale projects require longer time and higher production efficiency to achieve profitability.

To demonstrate the relationship between energy consumption and hydrogen production under different optimal scheduling strategies and evaluate the effect of varying scheduling strategies on improving hydrogen production efficiency, this paper analyzes the energy consumption and hydrogen production under the optimal scheduling strategies, and the results are shown in Figure 8.

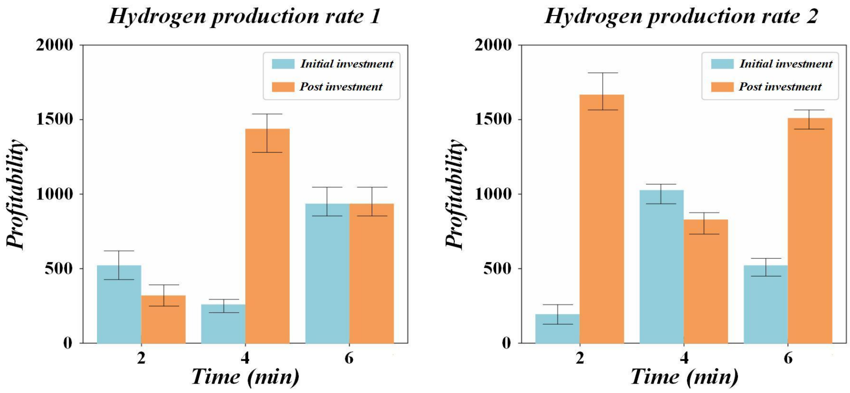

Figure 8. Analysis of energy consumption and hydrogen production under optimal scheduling strategy.

As can be seen from the figure, compared with the other two solutions, the intelligent algorithm energy-saving dispatching can achieve the highest hydrogen production (215,000 kg) and the lowest energy consumption (4700 MWh). The efficiency of this solution is improved by 20%, and the cost is reduced by 15%. Although multi-energy synergistic optimization also showed good hydrogen production (210,000 kg), the energy consumption was high (4800 MWh), and the efficiency was improved to 18%. However, the hydrogen production of demand forecasting dynamic scheduling is the lowest, only 200,000 kg, and the efficiency is improved to 15%. The data shows that reasonably optimized scheduling can significantly improve hydrogen production efficiency and reduce energy waste, thereby achieving dual cost reduction and hydrogen production improvements. Intelligent algorithm energy-saving scheduling is the best choice projects.

Table 5. Energy consumption and hydrogen production under different optimal scheduling strategies.

Scheduling strategy	Energy consumption (MWh)	Hydrogen production (kg)	Efficiency improvement (%)	Cost reduction (%)
Demand forecasting dynamic scheduling	5000	200000	15	10
Multi-energy collaborative optimization	4800	210000	18	12
Intelligent algorithm energy-saving scheduling	4700	215000	20	15

The energy consumption and hydrogen production under different optimal scheduling strategies are shown in Table 5. The table shows that the intelligent algorithm energy-saving scheduling can achieve the highest hydrogen production (215,000 kg) and the lowest energy consumption (4700 MWh) compared with the other two solutions. This solution improves hydrogen production efficiency (20%) and effectively reduces costs (15%). Although multi-energy collaborative optimization consumes less energy and increases hydrogen production, the benefits are still slightly inferior to intelligent algorithm energy-saving scheduling. Therefore, intelligent algorithm energy-saving scheduling is the best choice, suitable for large-scale production and long-term operation.

The wind power generation data comes from the on-site anemometers and SCADA systems of the studied wind farm, while the solar energy data comes from the heliometer and Vortex satellite dataset.

PEM, SOEIC, and HP&LP alkaline electrolysis cells are the main technologies for hydrogen production, each with different technical testing requirements. Key performance indicators include electrolysis efficiency, voltage stability, response time, thermal efficiency, and gas purity, which are crucial for evaluating the performance of each technology. Through precise technical testing and optimization, combined with the energy scheduling strategy of the wind solar coupling system, the stability and efficiency of hydrogen production can be improved, and data support can be provided for technology selection, thereby enhancing the overall performance and economy of the system.

5.Conclusion

Through in-depth research on the operation mode and optimal scheduling strategy of new energy hydrogen production, this paper discusses the important role of new energy in promoting renewable energy consumption and reducing carbon emissions. It proposes electrolysis water modeling methods optimal scheduling strategies. Through experiments and data analysis, this paper draws the following conclusions:

(1) The wind power coupled electrolytic water hydrogen generation system has significant advantages in solving the problem of new energy consumption. When a high proportion of new energy is connected, the system can effectively improve the accommodation capacity of wind power and reduce the phenomenon of wind and light abandonment. Simulation data show that when the wind power output exceeds 1000 MW, the system can absorb 20% -30% of the remaining power, reduce the wind rejection rate, and provide support for hydrogen energy storage and application. Especially in the winter wind power season, the wind power consumption rate can be

increased to more than 95%.

(2) The simulation results show that the optimal scheduling can reduce the overall operation cost of the system by 18%, improve the hydrogen production efficiency by 10%, and shorten the annual return on investment to 6.5 years. Through reasonable load dispatch, maximize the utilization of wind power surplus energy and improve the efficiency of wind power generation.

(3) The wind power coupled hydrogen generation system can significantly reduce carbon emissions, with an annual emission reduction of about 150,000 tons of CO_2, equivalent to the annual emissions of 30,000 fuel vehicles. The combination of carbon capture technology and natural gas system can further reduce carbon emissions and provide support for the transformation of low-carbon energy.

The wind power coupled hydrogen production system can significantly reduce carbon emissions, reducing approximately 150000 tons of carbon dioxide emissions annually, equivalent to the annual emissions of 30000 fuel vehicles. To evaluate the economic feasibility of the system, the levelized energy cost (LCOE) and levelized hydrogen cost (LCOA) were calculated. The estimated LCOE is 32.3 yuan/kWh, while LCOA is approximately 32.3 yuan/kgh $_2$, reflecting a significant reduction in production costs due to optimization of scheduling strategies and increased utilization of renewable energy. These results indicate that compared to traditional hydrogen production methods such as steam reforming, wind solar coupled hydrogen production systems have higher competitiveness and higher operational and environmental costs for steam reforming.

The proposed framework reduces operating costs by 18% and increases wind energy utilization to 95% in high resource scenarios. Compared to steam reforming, our system reduces 150000 tons of carbon dioxide emissions annually, in line with global decarbonization targets. Future work will integrate real-time policy adaptation and advanced carbon capture technologies.

The contribution electrolysis water to carbon emissions. Hydrogen storage with natural gas systems, the dependence on traditional fossil fuels is further reduced, providing strong support for the low-carbon transformation of the energy mix.

New energy hydrogen production technology, especially the wind power coupled electrolysis water hydrogen production system, can effectively promote renewable energy consumption, reduce the energy system's carbon emissions, and improve energy utilization efficiency. By optimizing the scheduling strategy, it can not only improve the economy of the system but also reduce carbon emissions during system operation, which has significant environmental benefits and social value. With the continuous advancement of technology and the further reduction of costs, hydrogen production from new energy sources way transition cope with climate change.

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Consent to Publish

The manuscript has neither been previously published nor is under consideration by any other journal. The authors have all approved the content of the paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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None

Author Contribution

Shilong Liu: Edited and refined the manuscript with a focus on critical intellectual contributions.

Chengbang Ma: Provided substantial intellectual input during the drafting and revision of the manuscript.

Conflicts of Interest

The authors declare that they have no financial conflicts of interest.

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