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ISSN 2959-6157

# Transformation and Utilization of Wind Power to Hydrogen Energy

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**Abstract:**
The accelerated global warming has prompted countries to commit to carbon neutrality (take the Paris Agreement as an example), and hydrogen energy has emerged as a crucial alternative to fossil fuels. With the global renewable energy sector booming, wind and solar power generation continues to expand. However, the widespread curtailment of wind and solar power has led to significant waste of clean energy resources. Converting excess electricity from these sources into hydrogen has emerged as a crucial approach to manage surplus power and optimize energy structures. This paper systematically examines the current status of wind-solar curtailment, provides detailed analyses of core conversion technologies including alkaline water electrolysis and proton exchange membrane (PEM) hydrogen production, and thoroughly evaluates technical, economic, and policy challenges in this field. Targeted development strategies are proposed to offer comprehensive guidance for advancing the hydrogen production industry utilizing wind-solar curtailment technologies.

**Keywords:** green hydrogen; renewable energy; wind power

## 1. Introduction

In recent years, driven by global climate action and energy transition trends, wind and solar power, as clean and renewable energy sources, have experienced rapid growth. China's 2023 figures show newly installed wind capacity at 56.44GW and photovoltaic capacity at 148.31GW, maintaining its position among the world's top in cumulative installations. However, persistent challenges like intermittent output from renewables and outdated grid infrastructure have led to chronic curtailment of wind and solar power. In 2022, regions with over 10% wind curtailment rates and around 5% solar curtailment rates highlighted that vast amounts of clean energy remained underused [1, 2].

Hydrogen energy, as a zero-emission and high-energy-density secondary energy source, is recognized as a crucial component of future energy systems. By converting wind and solar power curtailment into hydrogen, this approach not only effectively manages excess electricity but also provides clean fuel for transportation and industrial sectors, driving the transition to low-carbon and clean energy structures. Therefore, researching the conversion and utilization of wind-solar curtailment hydrogen holds significant practical importance. From the perspective of

ISSN 2959-6157

energy security, hydrogen production from wind-solar curtailment expands energy supply channels, reduces dependence on traditional fossil fuels, and enhances national energy security capabilities. In environmental protection, hydrogen's pollution-free production process helps reduce carbon emissions, improve ecological quality, and support the "Dual Carbon" goals. Economically, this technology drives related industries including hydrogen production equipment manufacturing, hydrogen storage and transportation, and hydrogen applications, creating new economic growth points and promoting industrial structure optimization. Furthermore, in-depth research on wind-solar curtailment hydrogen technology carries theoretical value for refining energy technology systems and advancing innovation in the energy sector [3].

In this context, this paper studies the technical routes and application scenarios of hydrogen production from wind and solar power abandonment, and proposes countermeasures for existing development challenges.

# 2. Current Situation of Wind Power Abandonment

## 2.1 Distribution and Installed Capacity of Wind Resources

China's wind energy resources are widely distributed with distinct regional characteristics. In terms of wind power, the "Three Norths" regions (Northeast, North China, and Northwest China) boast open terrain with annual average wind speeds reaching 6-8m/s, offering over 2 billion kilowatts of exploitable potential. The eastern coastal areas, influenced by maritime and land winds, are rich in offshore wind resources, with technically exploitable wind energy at 100-meter altitudes estimated at approximately 2.25 billion kilowatts. Solar energy resources are most abundant in western regions, where Xinjiang, Qinghai, and Tibet enjoy over 3000 hours of annual sunshine and high solar radiation intensity, providing ideal conditions for constructing large-scale photovoltaic power stations.

In recent years, China has witnessed rapid growth in wind and solar power installations. By the end of 2023, the cumulative installed capacity of wind power nationwide reached 391.98 GW, with onshore capacity at 341.49GW and offshore capacity at 50.49GW. The cumulative installed capacity of photovoltaic power reached 490.31GW, while distributed photovoltaic capacity surpassed 100 GW. These figures demonstrate China's remarkable achievements in renewable energy development, yet they also present significant challenges for effective electricity grid integration.

## 2.2 Wind and Light Curtailment Phenomenon and its Causes

Despite the continuous expansion of wind and solar power installations, the challenges of curtailed energy remain severe. Take Northwest China as an example. During winter heating seasons in some provinces, thermal power plants are prioritized to meet heating demands, squeezing the absorption capacity for wind and solar energy. This has resulted in wind curtailment rates reaching 15%-20%. There are three main reasons for the reduction in wind and solar power generation.

The absorption capacity of the power grid is insufficient: areas rich in wind and solar resources are often far away from power load centers, and the construction of transmission channels lags behind. For example, a large amount of wind and solar power in Inner Mongolia and Xinjiang cannot be transported to eastern provinces in time with large electricity consumption due to the lack of sufficient external delivery channels, so it has to be abandoned.

Wind and solar energy exhibit significant volatility: due to their output being heavily influenced by natural conditions, it results in strong intermittency and randomness. When wind and photovoltaic power sources dominate the grid, they can compromise stability and reliability. To ensure safe grid operation, power companies are compelled to implement power rationing measures, which ultimately leads to curtailment of electricity generation.

The power market mechanism is far from perfect: At present, China's power market has defects in resource allocation and price formation, and lacks effective incentive mechanism and compensation mechanism for power abandonment. When facing power abandonment, wind and solar power generation enterprises lack coping methods and cannot effectively absorb power through market channels.

# 3. Wind power to Hydrogen Energy Conversion Technology

## 3.1 Comparison of Hydrogen Production from Wind and Solar Power with other Energy Storage Schemes

According to Table 1, wind and solar power generation hydrogen production technology is one of the key ways to achieve large-scale energy storage, which can help reduce greenhouse gas emissions, improve ecological environment quality, and promote the realization of carbon peaking and carbon neutrality goals.

**Table 1. Comparison of Existing Energy Storage Schemes [1, 2]**

| Energy Storage Path | Transfer Efficiency | Energy Storage Duration | Potency | Environmental Impact | Application Scenarios |
|---|---|---|---|---|---|
| Wind Power to Produce Hydrogen | 30%~40% | Long Period | No | Zero Emissions (Green Hydrogen) | Large-scale Energy Storage, Industrial Hydrogen |
| Chemical Energy Storage (Lithium Battery) | 80%~90% | Short Cycle | No | Recycling Issues | Grid Frequency Modulation, Distributed Energy Storage |
| Pumped Storage | 70%~80% | Medium and Short Term | Terrain | Ecological Effect | Grid Load Regulation and Backup Power Supply |
| Compressed Air Energy Storage | 50%~60% | Medium Cycle | Geology | Low Emission | Large-scale Energy Storage and Grid Load Regulation |

### 3.2 Hydrogen Production Technology Roadmap

Hydrogen production is the current means to realize the conversion of wind and solar power into hydrogen energy. Its basic principle is that under the action of direct current, water is decomposed into hydrogen and oxygen. According to the different types of electrolytic cells, there are mainly three technologies:

Alkaline Electrolysis for Hydrogen Production: In alkaline electrolyte solutions (e.g., potassium hydroxide KOH or sodium hydroxide NaOH), hydrogen ions dissociate at the cathode to gain electrons and form hydrogen gas, while hydroxide ions at the anode lose electrons to produce oxygen and water. This technology, known for its mature development, cost-effective equipment, high reliability, and stability, has become the most widely adopted method in industrial applications. However, it faces limitations such as slow startup times (typically requiring tens of minutes to hours) and stringent water quality requirements (specifically demanding deionized water) [4].

Proton Exchange Membrane (PEM) Hydrogen Production: In PEM electrolyzes, water is decomposed at the anode using catalysts such as iridium (Ir) and other precious metal catalysts into oxygen, hydrogen ions, and electrons. The hydrogen ions migrate through the proton exchange membrane to the cathode, where they gain electrons to form hydrogen gas. The process is illustrated in Fig. 1. PEM hydrogen production offers advantages including high current density (up to 2-4 A/cm$^2$), rapid response capability (starting and power adjustment within seconds), and compatibility with renewable energy systems. However, it incurs higher manufacturing costs due to the material expenses of the proton exchange membrane and catalysts, while also requiring more durable catalysts [5-7].

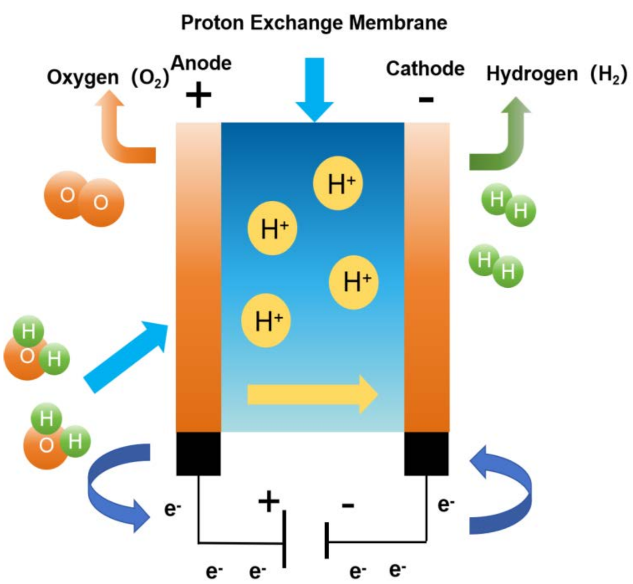


**Fig. 1. Internal structure of PEM electrolyzes [5]**

Solid Oxide Electrolysis for Hydrogen Production (SOEC): At high temperatures (700-1000℃), solid oxide electrolytes such as yttria-stabilized zirconia (YSZ) conduct oxygen ions. Water at the cathode is reduced to hydrogen, while oxygen ions at the anode generate oxygen. SOEC technology boasts advantages including high electrolysis efficiency (theoretical efficiency exceeding 90%) and effective energy conservation in hydrogen production. However, due to its high operating temperature, it requires materials and equipment with exceptional heat resistance, making technical challenges apparent. Currently, the technology remains in the laboratory R&D and small-scale demonstration phases [8-11].

### 3.3 Coupling Modes of Hydrogen Production

There are two main ways to couple wind power generation and hydrogen production.

ISSN 2959-6157

Direct coupling: This approach directly connects wind/solar power generation systems with hydrogen production facilities, utilizing surplus electricity to directly drive hydrogen production. The advantages include the simple system structure, high energy conversion efficiency, and reduced energy loss in intermediate stages. However, the significant volatility of wind/solar power requires extreme adaptability from hydrogen production equipment. When power input becomes unstable, it may compromise both the normal operation and service life of the equipment.

Indirect coupling: By utilizing energy storage systems (such as lithium battery storage and flow battery storage) to store renewable energy from wind and solar power, the system then supplies electricity to hydrogen production facilities based on actual demand. This approach effectively mitigates the intermittency and volatility of renewable energy generation, enabling hydrogen production equipment to operate under stable power conditions while enhancing operational efficiency and stability. Furthermore, through intelligent control systems that continuously monitor wind/solar power output, storage system status, and hydrogen production requirements, the system dynamically adjusts operational parameters of hydrogen production equipment. This achieves optimized coordination among wind/solar power curtailment, energy storage, and hydrogen production processes.

## 4. Hydrogen Energy Utilization Scenarios

### 4.1 Transport

In the transportation sector, hydrogen energy is primarily applied in hydrogen fuel cell vehicles. These vehicles use hydrogen as fuel and generate electricity through electrochemical reactions to drive the vehicle, offering advantages such as zero emissions, long driving ranges (typically 500-800 kilometers), and short refueling times (just 3-5 minutes). Currently, hydrogen fuel cell vehicles are rapidly developing in commercial vehicle applications, with extensive demonstration deployments in public transport, logistics vehicles, and heavy-duty trucks. For instance, during the Beijing Winter Olympics, over 1000 hydrogen fuel cell vehicles were deployed for event transportation services, achieving zero-carbon emissions in the transportation sector. Looking ahead, with technological advancements and improved infrastructure, hydrogen energy is expected to see widespread adoption in rail transit, maritime vessels, and aviation, driving comprehensive green transformation across the transportation industry.

### 4.2 Industrial Circle

Hydrogen energy holds vast application potential in industrial sectors. In the steel industry, traditional blast furnace ironmaking processes using coke as a reductant generate substantial carbon dioxide emissions. The adoption of Direct Reduction Iron (DRI) technology with hydrogen can substitute coke, directly reducing iron ore into iron to achieve low-carbon or even zero-carbon production. Currently, multiple global steel enterprises have launched pilot projects for DRI, such as Sweden's HYBRIT initiative, aiming to eliminate fossil fuel-based steelmaking by 2035. In the chemical sector, hydrogen serves as the fundamental raw material for critical products like ammonia and methanol. Utilizing wind/solar power-generated hydrogen for chemical production not only reduces manufacturing costs but also decreases dependence on fossil fuel-based hydrogen production, thereby lowering carbon emissions and enhancing the sustainable development capacity of the chemical industry. Additionally, hydrogen can replace conventional fossil fuels like natural gas and coal in high-temperature kilns of industries such as glass and ceramics, effectively reducing pollutant emissions including nitrogen oxides and sulfur dioxide.

### 4.3 Energy Storage and Grid Load Regulation

As a large-scale, long-term energy storage medium, hydrogen energy enables the transfer of electrical power across time and space, playing a vital role in grid energy storage and peak shaving (Table 2). During off-peak electricity demand periods, hydrogen can be produced from renewable energy sources like wind and solar power, which are then stored. During high load hours, stored hydrogen is converted back into electricity through fuel cell systems or other energy conversion devices, reintegrating it into the grid to balance load fluctuations. Compared with traditional battery storage, hydrogen storage offers advantages such as higher energy density, longer storage duration, and geographical flexibility. Furthermore, hydrogen storage systems can be integrated with other technologies (e.g., pumped hydro storage and battery storage) to create multi-energy complementary systems. This enhances the grid's capacity to accommodate renewable energy sources like wind and solar power while improving overall stability and reliability.

**Table 2. Applications and advantages of hydrogen production from wind and light in social fields [12, 13]**

| Domain | Application scenarios | Technology/Solution | Superiority |
|---|---|---|---|
| Transport | Hydrogen Fuel Cell vehicles | Hydrogen Gas Electrochemical Reaction Driven | Zero Emission, Long Range (500-800 km), Fast Hydrogenation (3-5 minutes) |
| Industrial Circle | Iron and Steel Industry | Direct Reduction of Iron with Hydrogen (DRI) Technology | Replace Coke, Reduce $CO_2$ Emissions, and Achieve Low Carbon/Zero Carbon Steel Making |
| | Chemical Lines | Green Hydrogen Used to Synthesize Ammonia and Methanol | Reduce Dependence on Fossil Fuels and Reduce Carbon Emissions |
| | High Temperature Process (Glass, Ceramics) | Hydrogen Instead of Natural Gas/Coal | Reduce Nitrogen Oxide and Sulfur Dioxide Emissions |
| Energy storage and Load regulation | Grid Energy Storage | Hydrogen Production by Electricity (Low Load) + Hydrogen Power Generation (High Load) | Long Term Energy Storage, High Energy Density, not Limited by Terrain |
| | Multi-energy Complementary System | Hydrogen Energy Combined with Wind Power and Pumped Storage | Improve the Stability of the Power Grid and Enhance its Capacity to Absorb Renewable Energy |

# 5. Challenges Existing and Development Strategies

## 5.1 Challenges

Technical Challenges: Current hydrogen production technologies face efficiency bottlenecks. Alkaline water electrolysis typically achieves 60%-70% efficiency, while proton exchange membrane (PEM) systems reach 70%-80%, leaving significant room for theoretical improvements. Moreover, domestic production levels of critical materials and equipment remain low, with core components like proton exchange membranes and high-performance catalysts predominantly relying on imports, driving up production costs. Additionally, hydrogen generation equipment requires enhanced stability and reliability during prolonged operation to withstand the extreme fluctuations of wind and solar power generation.

Economic Considerations: Hydrogen production projects utilizing wind and solar power curtailment face substantial investment costs, including hydrogen generation equipment, energy storage systems, and hydrogen storage and transportation infrastructure. It's estimated that constructing a hydrogen plant with a capacity of 1000 standard cubic meters per hour requires an investment of approximately 50-80 million yuan. Additionally, operational expenses during the hydrogen production process (including electricity costs, water usage fees, and equipment maintenance) remain high. Even when utilizing curtailed electricity, the production cost of hydrogen still struggles to compete with traditional fossil fuel-based methods after accounting for equipment depreciation. Currently, China's industrial by-product hydrogen prices range from 1.5 to 2 yuan per $Nm^3$, while the cost of hydrogen production through wind and solar power curtailment typically stands at 3-5 yuan per $Nm^3$.

Policy and Market Aspects: While China has implemented policies to support hydrogen energy development, the current framework lacks specificity and practicality in addressing wind/solar power curtailment-based hydrogen production. Key challenges include absence of clear electricity price subsidies for hydrogen production, an underdeveloped pricing mechanism, and inconsistent construction standards for hydrogen refueling stations, which hinder industry growth. Furthermore, China's hydrogen market remains small-scale with limited consumer demand. Public awareness and acceptance of hydrogen technology are still low, creating great obstacles for market expansion [14, 15].

## 5.2 Development Strategy

Strengthening R&D and Innovation: Increasing investment in hydrogen production technology development and supporting collaborative research initiatives between academic institutions and enterprises are needed. Prioritizing breakthroughs in key technical challenges such as efficiency enhancement and domestic production of critical materials, which includes developing advanced catalysts to improve electrolysis efficiency and creating cost-effective proton exchange membranes (PEM) is a must. Con-

ISSN 2959-6157

currently, conducting intelligent control system research for wind-solar power curtailment hydrogen production systems, achieving optimized coordinated operations across solar power generation, hydrogen production, and energy storage processes are required.
Improving the policy support system: The government should introduce targeted policies and measures, such as formulating electricity price subsidy standards for hydrogen production by abandoning electricity, and giving preferential electricity prices to enterprises that use wind and solar power to produce hydrogen. Meanwhile, authorities concerned ought to establish a reasonable hydrogen price formation mechanism, and reduce the cost of hydrogen production through fiscal subsidies and tax incentives.

## 6. Conclusion

As a crucial pathway for deep integration between renewable energy and hydrogen technology, wind-solar hydrogen production serves as a pivotal support for achieving the "dual carbon" goals and transforming the energy structure. This approach not only acts as a key solution to address renewable energy integration and grid peak shaving but also represents a strategic choice for reshaping the global energy situation. To advance its future development, it requires deep collaboration among industry, academia, and research institutions. By driving progress through technological innovation and institutional reforms, we can accelerate the transition from policy-driven to market-driven approaches in this field.

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