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Article

Policy Challenges and Applications of Hydrogen Energy and Energy Storage Technologies in Energy Transition

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Abstract: With the acceleration of the global energy transition process and the formulation of "carbon neutrality" goals by various countries, new energy means represented by hydrogen energy and energy storage technologies play a key role in building a low-carbon, safe, efficient and resilient energy system. Hydrogen energy can provide clean fuel for sectors that are difficult to reduce emissions, such as transportation, industry, and chemical engineering. Energy storage technology provides effective support for increasing the proportion of renewable energy and enhancing the resilience of the power system. However, although these technologies have achieved a certain degree of scale in the application stage, there are still problems in relevant policies such as the lack of standards, slow commercialization progress, incomplete infrastructure and unbalanced international cooperation. In response to the above situation, it is necessary to further ensure the smooth progress of hydrogen energy and energy storage technologies in the energy transition process through measures such as promoting demonstration projects, optimizing the marketization process, strengthening infrastructure construction and enhancing the level of international cooperation.

Keywords: hydrogen energy; energy storage; energy transition; policy challenges; application path

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1. Introduction

The de-fossilization and enhanced flexibility of the energy system, supported by hydrogen energy and energy storage technologies, represent core technological pathways for the sustainable development of future energy systems. As energy structures gradually shift toward low-carbon and diversified configurations, hydrogen energy and energy storage play increasingly important roles in balancing supply and demand, integrating renewable energy, and improving system resilience. However, in the process of technological evolution and deployment, technological maturity alone does not determine the success or scalability of these solutions. Instead, market systems and policy frameworks exert equally significant influences on their development trajectories and practical applications [1].

In particular, institutional arrangements such as technical standards, operational norms, and regulatory supervision directly affect cost formation and risk allocation, thereby shaping investment expectations and decision-making behavior. Reasonable and transparent standards can reduce uncertainty and transaction costs, while insufficient or inconsistent regulatory arrangements may hinder large-scale deployment [2]. At the same time, market mechanisms transmit assessments of economic benefits through price signals, guiding producers, consumers, and investors in allocating resources. If price signals fail to reflect actual system value or externalities, the diffusion of hydrogen energy and energy storage technologies may be distorted or delayed.

Infrastructure structure further determines the actual scale of utilization and spatial distribution of hydrogen energy and energy storage applications. The layout of production facilities, storage systems, and transmission networks constrains technological feasibility and operational efficiency, especially under conditions of regional imbalance in resource endowments and demand patterns. In addition, cross-regional market coordination and management influence the efficiency of resource allocation by affecting interregional trading, system interoperability, and operational scheduling. Fragmented market governance may lead to duplicated investments or underutilized capacity, while coordinated mechanisms can enhance overall system performance [3].

Therefore, the application of hydrogen energy and energy storage technologies exhibits a strong characteristic of institutional dependence, and adjustments in governmental regulatory arrangements can directly influence their practical application capacity and development pace. By systematically analyzing the interactions among technology, market mechanisms, and policy frameworks, potential obstructive factors in current systems can be identified. Such analysis provides a more solid analytical basis for optimizing institutional design, improving market coordination mechanisms, and promoting effective international cooperation in the sustainable energy transition [4].

2. The Strategic Role of Hydrogen Energy and Energy Storage in the Energy Transition

2.1. Key Functions of Hydrogen Energy in the Deep Decarbonization of Energy Systems

Under the premise of the accelerated pace of energy transition, hydrogen energy has become an important technical option for deep decarbonization due to its diverse sources, zero-carbon characteristics and strong application range. It is particularly important in transportation, chemical manufacturing and metal production where emissions cannot be reduced through electrification. Green hydrogen produced from renewable energy can achieve energy circulation in both time and space dimensions, increasing system flexibility to adapt to changes in supply and demand. To illustrate the role of hydrogen energy in the energy chain, Figure 1 structurally presents the main functions of hydrogen energy in production, storage and transportation, and terminal applications, which is helpful for understanding its overall role in the energy system.

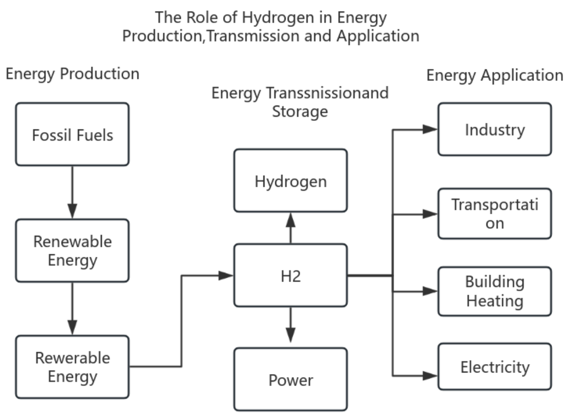

Figure 1. Schematic diagram of the multi-link role of hydrogen energy in the energy system.

Whether it is industrial hydrogen or its application in industries such as steel, petrochemicals, and transportation, they can all play a positive role in reducing the intensity of fossil energy use and mitigating carbon emissions. The promotion of hydrogen fuel in the transportation sector relies on the continuous improvement of hydrogen fuel cell vehicles in terms of energy replenishment efficiency, operational stability, driving range, and adaptability to cold environments. In the future, this will provide an economical and sustainable solution for long-distance freight transportation, port operation vehicles and high-intensity operation scenarios. To present the current application status and development trend of hydrogen energy in the form of data, the scale indicators of hydrogen energy in various fields are shown in Table 1.

Table 1. Key data of hydrogen energy in major application fields.

Application field	Hydrogen energy demand/scale	Annual growth rate	Typical country cases
Heavy-load transportation	150,000 tons per year	18%	Japan, South Korea
Refining and chemical industry	7 million tons per year	3%	European Union
Steel Industry (DRI)	500,000 tons per year	25%	Germany, Sweden
Consumption of hydrogen produced by electricity	1.2 million tons per year	35%	China

From a broader systemic perspective, the value of hydrogen energy is not entirely reflected in the "alternative energy" itself, but rather in its ability to replace traditional energy transmission methods through non-intermediary forms of conversion. As hydrogen can serve as a carrier for energy conversion among different energy sources, this mechanism can make the energy system more flexible and adaptable, and can be linked with power applications, thereby building a future diversified and multi-energy complementary system-type energy system.

2.2. The Supporting Role of Energy Storage in a High-Proportion Renewable Energy System

The continuous increase in the proportion of renewable energy has led to the unpredictability and instability of the power network. Therefore, using energy storage as a means to balance the instability of the power grid system and improve the effectiveness of energy control has become a core key. Energy storage devices can achieve stable energy supply under various conditions by relying on rapid feedback, energy conversion and additional services, effectively making up for the insufficient efficiency of renewable energy utilization. Nowadays, energy storage devices have made progress in various fields, such as lithium-ion batteries, pumped storage, air energy storage, and flow batteries. Among them, lithium batteries are the most commonly used due to their flexibility and relatively low cost. Pumped storage is responsible for long-term energy storage tasks, while new energy storage technologies have further expanded the flexibility of the system. Table 2 shows the comparison of global energy storage installed capacity.

Table 2. Data on Installed Capacity and Growth of Energy Storage in Major Countries around the World.

Country/Region	Installed capacity of energy storage (GW/GWh)	Annual growth rate	Leading technical route
China	37 GW / 85 GWh	55%	Lithium battery energy storage
The United States	17 GW / 45 GWh	40%	Lithium batteries + pumped storage
Europe	12 GW / 30 GWh	30%	Distributed energy storage system
Japan	6 GW / 15 GWh	12%	Household energy storage

3. The Main Policy Challenges of Hydrogen Energy and Energy Storage Technologies in the Energy Transition

3.1. Imperfection of the Standard System, Regulatory Framework and Safety Norms

Hydrogen energy and energy storage have dual industrial attributes, involving system standards for manufacturing, storage, transportation, battery safety, grid connection, etc. However, the standardization development process and regulatory intensity of various countries are not consistent, which leads to difficulties in equipment, certification, projects and collaborative management. At present, in the field of hydrogen energy, factors such as purity levels, electrolyzer testing, and life cycle assessment (LCA) have not yet been unified. In terms of energy storage, fire protection requirements and grid connection rules are still under improvement. This not only increases the cost of cross-border deployment but also intensifies institutional frictions in international collaboration. The quantitative comparison of standard maturity in major regions is shown in Table 3.

Table 3. Comparison of the maturity data of hydrogen energy and energy storage standards in China, the UK and Europe.

Project category	China (0-100)	United Kingdom (0-100)	European Union (0-100)
Maturity of hydrogen energy classification standards	60	85	90
Maturity of energy storage safety standards	65	80	88
Maturity of hydrogen quality standards	55	82	90
Maturity of the LCA carbon accounting system	50	78	88

3.2. The Commercialization Model Is Not Mature and the Market Revenue Mechanism Is Unstable

At present, the cost of hydrogen production mainly depends on the cost of renewable energy, the cost of large-scale manufacturing and government subsidies. The work of reducing the price of green hydrogen is still ongoing. Although energy storage technology is relatively mature, the feasibility of its commercial success remains rather fragile. For instance, changes in peak-valley electricity price differences, power auxiliary service revenues, and government subsidies can all make the profitability of related investments unstable. The refueling efficiency, refueling volume and equipment service life of hydrogen refueling stations will also affect the business model of hydrogen energy application. In terms of social capital, if the market mechanism cannot maintain stable operation in the long term, the enthusiasm of social capital to participate will also be suppressed. The relevant situation is shown in Table 4.

Table 4. Cost and Market Revenue Mechanism of Hydrogen Energy and Energy Storage.

Country/Region	Hydrogen energy cost (US dollars /kg)	Energy storage cost (US dollars /kWh)	Intensity of policy incentives	Market maturity
China	4.5	0.12	Medium	Moderately low
European Union	6.0	0.18	high	high
The United States	3.8	0.14	Very high	high
Japan	7.0	0.20	Medium	Medium

3.3. Insufficient Infrastructure Construction and Incomplete Policy Supporting Measures

Although the infrastructure for hydrogen energy is gradually improving, the uneven distribution of hydrogen refueling stations, small-scale hydrogen pipeline networks, and the high cost of storage equipment will still significantly restrict the transportation and industrial use of hydrogen. Meanwhile, due to the unclear regulations on power system access, land permit application and price system, there are differences among local governments in policy-making, making it difficult to form a comprehensive and organized promotion model. Due to the lack of overall comprehensive coordination, the degree of connection among industrial chains is relatively low. The relevant situation is shown in Table 5.

Table 5. Data on Hydrogen Energy and Energy Storage Infrastructure Construction.

Country/Region	The number of hydrogen refueling stations	Hydrogen pipeline network mileage (km)	Installed capacity of energy storage (GW)	Degree of policy support
China	450	200	37	Medium
The United States	120	160	17	Higher
Germany	140	400	8	Perfect
Japan	160	10	6	high

3.4. Asymmetry of International Cooperation Mechanisms and Bottlenecks in the Technology Supply Chain

The internationalization of the hydrogen energy and energy storage supply chain has led to differences among countries in terms of cooperation depth, standard consistency, and carbon accounting methods, increasing institutional barriers in multi-country demonstration projects and technological cooperation. The concentration of core equipment such as electrolyzers, battery materials and high-pressure hydrogen storage cylinders is relatively high, which also makes some countries rely to a certain extent on overseas markets in terms of supply chain security, further increasing the uncertainty of industrial development. The relevant situation is shown in Table 6.

Table 6. Concentration of Supply Chain for Key Equipment of Hydrogen Energy and Energy Storage.

Equipment type	Global CR5 (%)	Chinese share	Degree of dependence on the European Union	Degree of dependence on the United Kingdom
Electrolyzer (PEM)	75	35%	65%	60%
Battery materials (lithium, nicke)	80	60%	70%	68%
High-pressure hydrogen storage cylinder	70	40%	50%	55%
Hydrogen compression equipment	65	30%	55%	58%

4. Policy Paths for the Application of Hydrogen Energy and Energy Storage Technologies in Energy Transition

4.1. Strengthen the Low-Carbon Role of Hydrogen Energy and Energy Storage through Policy Positioning and Demonstration Promotion

Infrastructure is the key for hydrogen energy and energy storage to move from experimentation to large-scale application. The construction level of hydrogen refueling stations, hydrogen storage equipment and regional hydrogen pipeline networks directly affects their promotion in the transportation and industrial fields. However, at present, they are still restricted by factors such as high costs, high safety regulations and complex approval processes. The reliability and availability of the hydrogen supply system can be enhanced through regionalized planning and cluster layout. In terms of energy storage, the peak shaving and frequency regulation capabilities of the system are determined by the energy storage power station, grid connection and the regulation platform. In engineering evaluation, the energy conversion characteristics of energy storage are often measured by the comprehensive round-trip efficiency, which reflects the losses of inverters, batteries and auxiliary systems. The expression is as follows:

$$E = Q(H_2) \times EF - E \quad (1)$$

Here, E is emission reduction, Q is hydrogen use, EF is the carbon emission factor of the substituted energy, and E is the emissions from hydrogen production. Demonstration projects promote coordinated industrial-chain development: in hydrogen, they drive progress in electrolyzers, storage containers, and fuel cell systems; in energy storage, they support battery, energy management, and safety technology upgrades. As demonstration projects scale up, cost reduction and technological improvement accelerate, paving the way for commercialization.

4.2. Promote the Large-Scale Development of Hydrogen Energy and Energy Storage through Strategic Planning and Market Mechanisms

Large-scale hydrogen and energy storage deployment requires integrated planning and a stable market model. National and regional plans should coordinate technology routes, industrial layout, and infrastructure such as transport networks and energy hubs. In the market, energy storage needs to operate as an independent asset earning returns through capacity pricing, ancillary services, and real-time bidding, while hydrogen benefits from green product attributes, carbon trading, and peak-shaving incentives. Economic feasibility can be assessed through metrics like cost per kilowatt-hour and hydrogen production cost to evaluate how planning and market mechanisms reduce overall costs.

$$LCOH = \frac{C_{CAPEX} \times r + C_{OPEX} + C_{electricity}}{\text{Annual Hydrogen Production}} \quad (2)$$

C_{CAPEX} is the initial investment of the hydrogen production system, r the capital recovery coefficient, C_{OPEX} the O&M cost, and $C_{electricity}$ the annual electricity expense. Electricity market reform-through transparent pricing, stronger spot trading, and expanded ancillary services-is key to improving energy storage economics. For hydrogen, market mechanisms must match the industrial chain. Integrating data and value flows from production to use enables wider applications in transport, industry, and power.

4.3. Rely on Infrastructure Construction to Promote the Engineering Implementation of Hydrogen Energy and Energy Storage

Infrastructure is the key for hydrogen energy and energy storage to move from experimentation to large-scale application, and its completeness directly affects the penetration capacity in fields such as transportation and industry. In engineering evaluation, the energy conversion performance of energy storage is usually measured by the comprehensive round-trip efficiency, which simultaneously reflects the losses of the inverter, battery and auxiliary system. The expression is as follows:

$$\eta_{rt}=\eta_{inv}\times\eta_{batt}\times(1-\lambda_{aux}) \quad (3)$$

Among them, η_{inv} represents the inverter efficiency, η_{batt} represents the battery charging and discharging efficiency, and λ_{aux} indicates the proportion of auxiliary system losses (temperature control, monitoring, line loss, etc.). The three together determine the comprehensive round-trip efficiency η_{rt} of the energy storage system. The contribution of energy storage in reducing the peak pressure of the system can be quantified by the peak shaving contribution rate, which reflects the relative extent of the decrease in peak load after the intervention of energy storage. Its expression is as follows:

$$PR=\frac{P_{peak}^{before}-P_{peak}^{after}}{P_{peak}^{before}} \quad (4)$$

Among them, P^{before}_{peak} and P^{after}_{peak} respectively represent the peak load of the system before and after the energy storage is connected. The obtained value PR can be used to characterize the peak shaving effect of the energy storage. The high comprehensive round-trip efficiency and peak shaving contribution rate both indicate that the energy storage infrastructure performs well in engineering operation. With the improvement of the monitoring system, the unification of access standards and the continuous accumulation of operational data, the reliability and adaptability of hydrogen energy and energy storage infrastructure will be further enhanced, laying a more solid foundation for their large-scale application.

4.4. Deepen the Cross-Border Application of Hydrogen Energy and Energy Storage through International Cooperation and Joint Demonstrations

The development and deployment of hydrogen energy and energy storage are inherently global, and standardized on-chain equipment systems rely heavily on cross-border coordination. International collaboration helps regions test new technologies, reduce project risks, and form replicable cases, while promoting consistency in certification, testing, and carbon accounting to lower the institutional costs of cross-border deployment. At the implementation level, countries' natural resources and technological strengths are complementary. Joint experiments can improve overall system performance, strengthen equipment interoperability and industrial chain integration, and support the globalization of operation and maintenance networks, creating a stronger foundation for large-scale commercial applications.

As shown in Table 7, the scale, participants, and characteristics of current cross-border alliances are already clear, offering insight into the deeper features and collaboration models of international experiments. Going forward, cooperation should emphasize unified standards, shared test facilities, and high-quality demonstration projects. These measures can accelerate international exchange, enhance the performance and reliability of hydrogen and storage technologies, and support broader cross-border deployment.

Table 7. Key Quantitative Indicators of International Cooperation Demonstration Projects.

Project Number	Number of cooperating countries (in)	Facility scale (MW)	Annual hydrogen production capacity (tons)	Number of participating institutions (in)	Number of standard mutual recognition items (units)	Number of demonstration vehicles/equipment (units)
1	2	5	800	6	1	80
2	3	10	0	8	2	0
3	2	5	800	5	0	0
4	3	0	0	7	3	0

5. Conclusion

The rapid advancement of hydrogen energy and hydrogen storage technologies is reshaping the existing energy system. Energy policies are shifting from traditional supply-oriented control to more flexible, coordinated, and cross-departmental regulation. As demonstration projects accumulate experience, costs continue to decline, and regulatory systems improve, hydrogen technologies will be applied in a broader range of scenarios. The widespread adoption of hydrogen energy depends not only on technological progress but also on institutional reform, planning guidance, and effective departmental collaboration. Its development requires building open technological application networks, improving data and standard consistency, and establishing an inclusive policy framework that encourages multi-party participation. With these conditions gradually in place, hydrogen energy will play an increasingly important role in optimizing the energy structure and driving related industrial development.

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