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Problems And Suggestions Regarding Hydrogen Energy As a Sustainable Energy Source

Zilong Zhao

International Institute of Management and Business,220086, Minsk City,Belarus

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ABSTRACT

As the world accelerates toward the goal of "carbon neutrality," the green transition of energy systems has become an inevitable choice for addressing climate change. Hydrogen energy, with its unique characteristics, is regarded as the "fourth-generation energy" following coal, petroleum, and electricity, playing a crucial role in solving energy and environmental challenges. From Germany's "National Hydrogen Strategy" to Japan's vision of a "Hydrogen Society," and from China's "14th Five-Year Plan" for the hydrogen energy industry to the EU's "Hydrogen Corridor" initiative, major global economies have elevated hydrogen energy to a national strategic level. The primary objective of this article is to enhance public understanding and knowledge of hydrogen energy, thereby promoting its greater role in sustainable energy systems. The focus of this paper lies in addressing the high costs associated with hydrogen energy transportation and storage.

INTRODUCTION

Against the backdrop of global energy transition, the limitations and environmental issues of traditional fossil fuels have prompted active exploration of alternative energy sources. Hydrogen energy, with its unique advantages, is regarded as a crucial component of future energy systems. Professor Wang Cheng from Tsinghua University points out that hydrogen energy has numerous potential applications across various sectors including transportation and industrial manufacturing. Jonas Moberg, CEO of the Green Hydrogen Organization (GH2), believes green hydrogen can be applied in fertilizer production, maritime shipping, and industrial processes, serving as a vital means to drive societal decarbonization. These perspectives demonstrate that hydrogen energy will emerge as a sustainable energy source, with its significance summarized as follows [1]:

1) Addressing climate change and environmental protection: reducing greenhouse gas emissions and mitigating air pollution;
2) Enhancing energy security and independence: decreasing reliance on imported fossil fuels and improving energy supply stability;
3) Promoting energy transition and sustainable development: facilitating efficient utilization of renewable energy and building a diversified energy system;
4) Economic and industrial development: creating new economic growth opportunities and driving transformation and upgrading of traditional industries;
5) Social and livelihood benefits: improving equitable access to energy and enhancing the efficiency and quality of energy utilization.

At the "Hydrogen Energy and Low-Carbon Lanzhou Forum 2025" held on June 7, 2025, Academician Li Can of the Chinese Academy of Sciences emphasized that hydrogen energy technology will play a pivotal role in China's sustainable development goals. It is not only a key technology for achieving the "dual carbon" targets but also a driving force behind the green and low-carbon transformation of the entire industrial system [2]. He highlighted that large-scale hydrogen production in the future will primarily address decarbonization needs in industries such as steel, metallurgy, cement, and chemicals

* Corresponding author. E-mail address:13911573103@163.com

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— sectors currently reliant on fossil fuels but poised to transition toward hydrogen to achieve low or even zero carbon emissions. Academician Li Can's team has made breakthroughs in hydrogen storage materials, developing composite metal materials with hydrogen absorption exceeding 8% while reducing hydrogen release temperatures from 250° C to 90° C.

Globally, hydrogen energy is undergoing dual acceleration from policy consensus to technological breakthroughs. In 2023, global hydrogen demand reached 97 million tons, yet green hydrogen accounted for less than 2%, with fossil fuel-based production still dominating [3]. Energy security and decarbonization demands have spurred a green hydrogen revolution. Countries like Germany and the Netherlands are securing green hydrogen supplies through import strategies targeting North Africa and Australia, while China leverages its affordable photovoltaic resources to build a "hydrogen economy corridor." Concurrently, technological advancements are driving costs toward critical thresholds: in 2025, alkaline electrolyzer prices dropped by 38% year-on-year, and PEM electrolyzers by 29%, bringing green hydrogen levelized costs close to the parity benchmark of 15 RMB/kg.

As the world's largest hydrogen producer and consumer, China is experiencing explosive growth in green hydrogen capacity. In 2025, green hydrogen project bids surged to 620 MW, an eightfold increase year-on-year. Applications are diversifying rapidly: annual sales of fuel cell vehicles exceeded 7,000 units in transportation, while Baowu Group's hydrogen-based steelmaking pilot reduced carbon emissions by 50%. By September 2024, China had commissioned 500 hydrogen refueling stations — the highest globally — and accounted for over 50% of the world's cumulative renewable hydrogen production capacity (exceeding 250,000 tons/year).

In April 2025, China completed its first hydrogen-ammonia-methanol integrated project in Yantai, Shandong Province, which utilizes offshore renewable energy for off-grid hydrogen production and converts it into more easily storable ammonia and methanol. The EU's Carbon Border Adjustment Mechanism (CBAM) is driving the adoption of green hydrogen through carbon pricing, with this "subsidy + carbon pricing" dual approach accelerating the commercialization of green hydrogen. Sinopec's "West-to-East Hydrogen Transmission" project complements Europe's HyDeal Ambition initiative, creating a coordinated development pattern between East and West [4].

It is evident that hydrogen energy, as a sustainable energy source, is demonstrating positive development trends both domestically and internationally. However, several challenges remain, including high production and transportation costs, technological bottlenecks, inadequate infrastructure, and lack of unified standards and regulations.

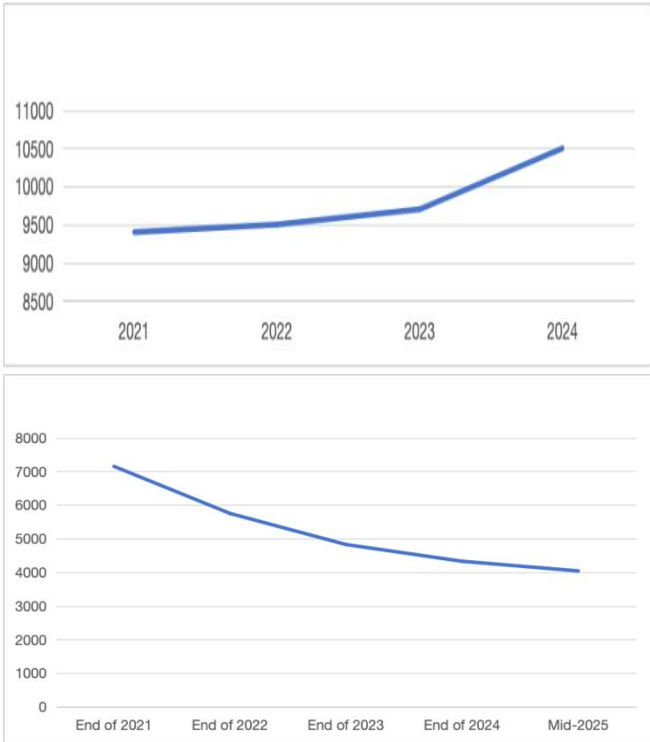

Fig.1. The following charts present global hydrogen energy production and price trends

Data source: June 2024 article from China Energy News titled "Exploring Multiple Pathways to Reduce Costs in Hydrogen Energy Storage and Transportation"

1.Hydrogen Production Methods and Storage/Transportation Technologies

The research team led by Lü Zhihui in Yulin, China has achieved scaled production of magnesium hydride (MgH_2) hydrogen storage materials, reducing hydrogen storage and transportation costs by 25%. In the United States, Dr. Barbara Kutchko has pioneered underground hydrogen storage sealing technology, developing novel cement-based sealing materials that ensure both safety and cost-effectiveness when utilizing salt caverns and depleted oil/gas reservoirs for hydrogen storage [5].

The Australian research team headed by Charles Johnston conducted a systematic economic comparison of different hydrogen carriers (ammonia, methanol, and liquid hydrogen),

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with study results indicating ammonia as the most cost-effective transportation medium at $0.56/kg H_2 . Detailed comparative analysis is presented in the following chart:

Type	Cost Characteristics	Related Notes
Magnesium hydride (MgH_2) based hydrogen storage and transportation materials	Single hydrogen storage cost below 0.5 RMB/kg	Magnesium-based solid-state hydrogen storage technology demonstrates high storage density, reaching 7.6 wt%. With the construction of 10,000-ton production lines, the cost of magnesium hydride material is expected to decrease from 1,000 RMB/kg to 300 RMB/kg.
Underground hydrogen storage sealing technology	The initial construction cost is relatively high, while the long-term storage cost is comparatively low.	Underground hydrogen storage solutions, such as salt cavern storage, are well-suited for large-scale, long-duration hydrogen storage. Substantial upfront investment is required for cavern development and related engineering work. For example, the Yexian Salt Cavern Hydrogen Storage Project in Henan Province involved a total investment of over 70 million RMB. However, due to its excellent sealing performance and high capacity, this method offers relatively low unit hydrogen storage costs in the long term.
Ammonia (NH_3) mediated hydrogen transportation	The current cost is projected at 720-1,400 /t, with potential future reduction to 310-610/t.	Ammonia exists in liquid form at ambient temperature, enabling cost reduction through utilization of existing transportation infrastructure. However, due to its toxic and corrosive properties, safety assurance costs remain elevated. For transportation distances ranging from 1,500 to 3,500 kilometers, maritime ammonia shipping demonstrates cost advantages.
Methanol (CH_3OH) based hydrogen logistics	Transportation costs account for approximately 15-30% of the total price	Methanol remains in liquid state at ambient temperature and can be transported via road, rail, or maritime shipping, with maritime transportation offering the lowest unit cost。
Cryogenic liquid hydrogen (LH_2) transportation	Large-scale liquefaction entails high energy consumption and elevated costs, yet economies of scale can drive cost reduction.	Liquid hydrogen transportation requires cryogenic conditions and stringent thermal insulation for containers. Significant capital investment and high energy consumption characterize liquefaction plant operations. At transportation distances of 500 kilometers, the distribution cost increases by only $0.3/kg, demonstrating advantages for long-distance transport. With liquefaction capacity expansion to 150 tons/day, the energy consumption for liquefaction can be reduced to 6 kWh/kg, resulting in lower overall costs.

Table.1. Economic Comparison of Hydrogen Transportation Methods

Source: Chapter 3 - Hydrogen Production, Storage and Transportation, Hydrogen Energy and Fuel Cell Technology Towards Carbon Neutrality [6-9]

Discussion of hydrogen energy storage and transportation inevitably involves hydrogen production methods. Current primary methods include: electrolytic water hydrogen production, fossil fuel-based hydrogen production, biological hydrogen production, and photolytic water hydrogen production.

Hydrogen storage methods primarily include three types: high-pressure gaseous storage, cryogenic liquid storage, and solid-state storage. High-pressure gaseous storage is currently the most commonly used and mature method, primarily employing sealed pressure vessels for hydrogen storage. This method offers advantages such as simple storage equipment and fast charging/discharging speeds, but its relatively low storage density and requirement for large storage space remain issues to be addressed. The table below shows current cost comparisons of these three hydrogen storage methods in China:

Storage Methods	Transportation Distance and Cost Analysis	Cost Description
High-Pressure Gaseous Hydrogen Storage	When the transportation radius exceeds 300 km, the transportation cost is 35 RMB/kg	Core materials such as carbon fiber rely on imports, resulting in high hydrogen storage tank costs. For 20MPa gaseous hydrogen tube trailers, the average cost increases by 3.44 RMB/kg per additional 100 km，Calculated based on 5,000 charge-discharge cycles, the hydrogen storage cost per kilogram is 1.2 RMB.
Cryogenic Liquid Hydrogen Storage	When the transportation distance increases from 50 km to 600 km, the cost for 30 t/d liquid hydrogen tank trucks rises from 5.89 RMB to 7.37 RMB/kg, with an average cost increase of 0.27 RMB/kg per additional 100 km.	The liquefaction energy consumption per kilogram of hydrogen is as high as 12-15 kWh, leading to high energy costs, The price of one liter of liquid hydrogen is approximately 30-40 RMB.
Solid-State Hydrogen Storage	Under 500 km transportation scenarios, the cost is approximately 20 RMB/kg, which is 43% lower than high-pressure gaseous storage.	The current cost of hydrogen storage tanks is about 1,200 RMB/L, With technological advancements and economies of scale, the cost is decreasing at an annual rate of 15%. If magnesium-based materials achieve 100% recycling, the cost will decrease significantly.

Table.2. Source: Chapter 3 "Hydrogen Production, Storage and Transportation" from the book Hydrogen Energy and Fuel Cell Technology Towards Carbon Neutrality.

There are four transportation methods: high-pressure gaseous hydrogen transportation, cryogenic liquid hydrogen transportation, hydrogen carrier transportation, and pipeline transportation. High-pressure gaseous hydrogen transportation involves delivering compressed hydrogen to destinations via high-pressure hydrogen cylinders or tube trailers. This method is suitable for short-distance, small-batch hydrogen transportation, offering high flexibility, but with relatively elevated costs. Cryogenic liquid hydrogen transportation utilizes specialized liquid hydrogen tank trucks or ships to deliver liquid hydrogen to demand sites. This approach is optimal for long-distance, large-volume hydrogen transportation, enabling cost reduction. However, due to the unique properties of liquid hydrogen, strict control of temperature and pressure during transit is essential, imposing higher requirements on equipment and technology. Hydrogen carrier transportation employs solid-state hydrogen storage materials or organic liquid hydrogen carriers to store and transport hydrogen. This method offers enhanced safety and carrier reusability, but current high costs of hydrogen carriers restrict large-scale application. Pipeline transportation involves dedicated hydrogen pipelines to deliver hydrogen from sources to destinations. This method offers advantages such as low cost, continuous operation, and high throughput, making it suitable for long-distance, large-scale hydrogen transportation.

Transportation Methods	Transportation Costs	Technical Specifications
High-Pressure Gaseous Hydrogen Transportation	At a transportation distance of 50 km, the cost is approximately 4.9 RMB/kg; at 500 km, it is about 22 RMB/kg	Tube trailers are typically employed, with 200 km being the cost-effective distance. Costs are highly distance-dependent and increase significantly with longer distances.
Cryogenic Liquid Hydrogen Transportation	At a transportation distance of 100 km, the cost is approximately	Liquid hydrogen tanker transportation is suitable for long-distance, high-capacity storage and transport.

	13.57 RMB/kg; at 500 km, it is about 8.85 RMB/kg	
Hydrogen Carrier Transportation	At a transportation distance of 50 km, the cost is approximately 9.6 RMB/kg; at 1000 km, it is about 21.7 RMB/kg	As transportation distance increases, costs rise due to factors such as hydrogen consumption during charging/discharging and equipment depreciation.
Pipeline Transportation	Per 100 km, the cost increases by approximately 1.3-1.5 RMB/kg	This method is optimal for long-distance, large-scale transportation and is currently the most efficient hydrogen delivery method. While initial pipeline construction costs are high, the long-term amortized costs are the lowest.

Table.3. Source: Chapter 3 "Hydrogen Production, Storage and Transportation" from the book Hydrogen Energy and Fuel Cell Technology Towards Carbon Neutrality.

2.Recommendations for Hydrogen Energy as a Sustainable Energy Source in Storage and Transportation

In light of the current challenges faced by hydrogen energy across various application domains, particularly in transportation and storage, the following recommendations are proposed:

2.1.Enhance Cost Management

Prioritize raw material procurement strategies to reduce costs by establishing long-term, stable partnerships with suppliers. Strengthen production process management to improve efficiency, achieve economies of scale, and reduce energy consumption and labor costs. Rationalize the planning of transportation and storage segments, optimize transport routes where possible, and achieve cost savings. Based on current practical conditions, it is recommended to use low-cost, reusable carbon fiber hydrogen storage tanks for storage, and to utilize existing pipelines or blended hydrogen pipelines for transportation. If vehicle transportation is necessary, actively develop 35MPa hydrogen transportation technology and limit the delivery distance to within 300 kilometers.

2.2.Promote Technological Innovation

Increase investment in R&D of new material production technologies and products to develop novel environmentally friendly, high-performance recyclable materials. Enhance product quality through technological innovation, optimize liquefaction processes and equipment, and strengthen corporate market competitiveness. Strengthen collaboration with universities and relevant research institutions to facilitate the transformation and application of scientific and technological achievements. For hydrogen storage materials, it is recommended to use magnesium-based composite materials, leveraging the synergistic effects of nanonization and catalysts to reduce hydrogen absorption/desorption temperatures and increase storage capacity; For transportation, it is recommended to employ IoT and big data technologies for real-time monitoring and management of hydrogen storage equipment and transportation processes, enabling remote equipment monitoring, fault early warning, maintenance optimization, improved operational efficiency, and reduced maintenance costs.

2.3.Foster Industrial Chain Synergy Effects

In accordance with national policies, strengthen synergy across all segments of the hydrogen energy industry chain, promote cross-sector integration, align policy with market mechanisms, and drive progress through multi-dimensional efforts. Integrate the entire chain of "production-storage-transportation-refueling-application" to establish a virtuous cycle of "expanding application scale → reducing hydrogen production costs → further advancing application adoption". Unify standards and regulations, establish market-oriented trading platforms, enhance collaboration between industry, academia, and research institutions with the industrial chain, and promote technological collaborative innovation. It is recommended to form a hydrogen energy industry alliance, with policies guiding regional specialization, to achieve efficient coordination, reduce overall costs, expand application scale, and unleash synergistic effects. Plan storage and transportation solutions rationally based on hydrogen production output and demand to reduce overall costs.

2.4.Promote Green Development Initiatives

Actively respond to sustainable development requirements by utilizing hydrogen energy as an energy carrier, integrating it with power, heating, transportation, and other systems to form a multi-energy complementary system of "hydrogen-electricity-heat-storage," promoting low-carbon transformation of the energy structure, facilitating deep decarbonization in the industrial sector, and optimizing green mobility in transportation. Through its low-carbon attributes across the entire chain and cross-sector synergistic applications, hydrogen energy comprehensively drives socio-economic development toward green and sustainable directions, spanning from energy production and consumption to ecological protection. It is recommended to deploy green hydrogen projects in regions abundant with wind and solar resources, integrate hydrogen production with pipeline transportation planning, and adopt large-scale pipeline transportation to not only reduce transportation costs but also avoid carbon emissions during transit, achieving truly sustainable green energy through green hydrogen production and green transportation.

Conclusion

Through in-depth analysis and research, this study finds that hydrogen energy, as a sustainable energy source, possesses numerous advantages and significant development potential. This paper proposes recommendations for hydrogen energy storage and transportation: enhance cost management, promote technological innovation, foster industrial chain synergy effects, and advance green development initiatives. Establish a hydrogen energy industry alliance to unleash industrial synergy effects, deploy green hydrogen projects in regions abundant with wind and solar resources, integrate hydrogen production and pipeline transportation planning, utilize magnesium-based composite materials for hydrogen storage, prioritize blended hydrogen pipeline transportation where feasible, employ 35MPa hydrogen transportation technology for vehicle transport with distances limited to 300 kilometers, and implement real-time monitoring through IoT and big data technologies. Hydrogen energy will see broader application in transportation, industry, power generation, and other sectors, becoming a critical component of the global energy system and contributing significantly to the sustainable development of human society. Countries should strengthen cooperation and exchange, jointly promote the research, development, and innovation of hydrogen energy technologies, accelerate the growth of the hydrogen energy industry, and achieve global green development of hydrogen energy.

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