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Research on Storage and Transportation Cost Control and Technological Breakthroughs from the Perspective of Global Hydrogen Energy Development

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KEYWORDS

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Techno-Economic Analysis;
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ABSTRACT

As the world accelerates towards the "carbon neutrality" goal, the green transformation of the energy system has become an inevitable choice in addressing climate change. Hydrogen energy, with its unique characteristics, is regarded as the "fourth-generation energy" following coal, oil and electricity, and plays a crucial role in addressing energy and environmental challenges. Germany, Japan, China, the European Union and other countries have all elevated it to a national strategy. This article focuses on the high cost issue of hydrogen storage and transportation, clarifies the cost differences among various storage and transportation technologies (high-pressure gaseous, cryogenic liquid, magnesium-based solid-state hydrogen storage, and ammonia/methanol carrier transportation), determines the optimal applicable scenarios for each technology, and provides solutions to reduce storage and transportation costs. This study employs a technical and economic comparison analysis method. Based on the cost data of hydrogen storage and transportation technologies (such as magnesium-based hydrogen storage costs and transportation costs over different distances) and technical parameters, it comparatively analyzes the economic performance of various technologies under different transportation distances and scales. Suggestions such as giving priority to hydrogen blending in existing pipelines and developing 35MPa road transportation can effectively reduce the cost of hydrogen storage and transportation, facilitate the large-scale application of hydrogen in transportation, industry and other fields, and provide support for the integration of hydrogen into the global sustainable energy system.

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

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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—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. This technology has been verified in laboratory-scale hydrogen storage devices, and the hydrogen storage density and release temperature indicators are better than the traditional metal hydride materials (hydrogen absorption rate <6%, release temperature >200°C) mentioned in the industry, laying a foundation for reducing the cost of solid-state hydrogen storage.

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]. To further clarify the gap between green hydrogen and traditional hydrogen, taking China as an example, in 2025, China's green hydrogen production capacity accounted for over 50% of the world's cumulative renewable hydrogen production capacity (exceeding 250,000 tons/year), but the proportion of green hydrogen in China's total hydrogen consumption is still less than 5%, which is consistent with the global green hydrogen penetration level . 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 (LCOH) close to the parity benchmark of 15 RMB/kg. Calculated based on the green hydrogen production cost of 15 RMB/kg and the transportation cost of different technologies (such as 35 RMB/kg for high-pressure gaseous hydrogen transportation over 300km), the delivered cost of green hydrogen in long-distance scenarios is still 2-3 times that of natural gas, which is the core constraint for the large-scale application of green hydrogen. As the world's largest producer and consumer of hydrogen energy, China's green hydrogen production capacity has seen explosive growth. By 2025, the annual sales of fuel cell vehicles in China will exceed 7,000 units, and the carbon reduction of the hydrogen-based steelmaking pilot project of Baowu Group will reach 50%. As of September 2024, China has built 500 hydrogen refueling stations, ranking first in the world in terms of quantity. The cumulative annual production capacity of renewable hydrogen has exceeded 250,000 tons, accounting for more than 50% of the global total. In April 2025, China completed its first "hydrogen-ammonia-methanol" integrated project in Yantai, Shandong Province. The project uses offshore renewable energy to produce hydrogen off-grid and converts hydrogen into ammonia and methanol, which are easier to store. The EU's Carbon Border Adjustment Mechanism (CBAM) promotes the application of green hydrogen through carbon pricing. This dual mechanism of "subsidies + carbon pricing" accelerates the commercialization of green hydrogen. The "West-to-East Hydrogen Transmission" project of Sinopec complements the HyDeal Ambition plan of Europe, building a coordinated development pattern between the East and the West [4].

Obviously, hydrogen energy, as a sustainable energy source, is showing a positive development trend both at home and abroad. However, it still faces challenges such as high production and transportation costs, technical bottlenecks, insufficient infrastructure, and inconsistent standards and regulations.The following chart shows the changes in global hydrogen production and prices (**Table 1** and **Table 2**).

Table 1 | Global Hydrogen Production Statistics Table from 2021 to 2024

Year	2021	2022	2023	2024
Global Hydrogen Production (10,000 tons)	9400.00	9500.00	9700.00	10500.00

Note: The data shows a steady growth trend of global hydrogen production, with an average annual growth rate of 3.6% from 2021 to 2024. The growth in 2024 is mainly driven by the increase in green hydrogen production in China and the EU (derived from the original text's 2025 green hydrogen project data and electrolyzer cost reduction information).

Table 2 | Global Average Price Statistics of Green Hydrogen from the end of 2021 to mid-2025

Time Point	End of 2021	End of 2022	End of 2023	End of 2024	Mid-2025
Average Price (US dollars/ton)	7150.00	5750.00	4825.00	4327.00	4040.00

Note: The average price of green hydrogen has decreased by 43.5% from the end of 2021 to mid-2025, mainly due to the decline in electrolyzer prices (38% year-on-year for alkaline electrolyzers in 2025) and the increase in scale of green hydrogen projects (8-fold year-on-year increase in China's green hydrogen project bids in 2025) (directly based on the original text's price and project data).

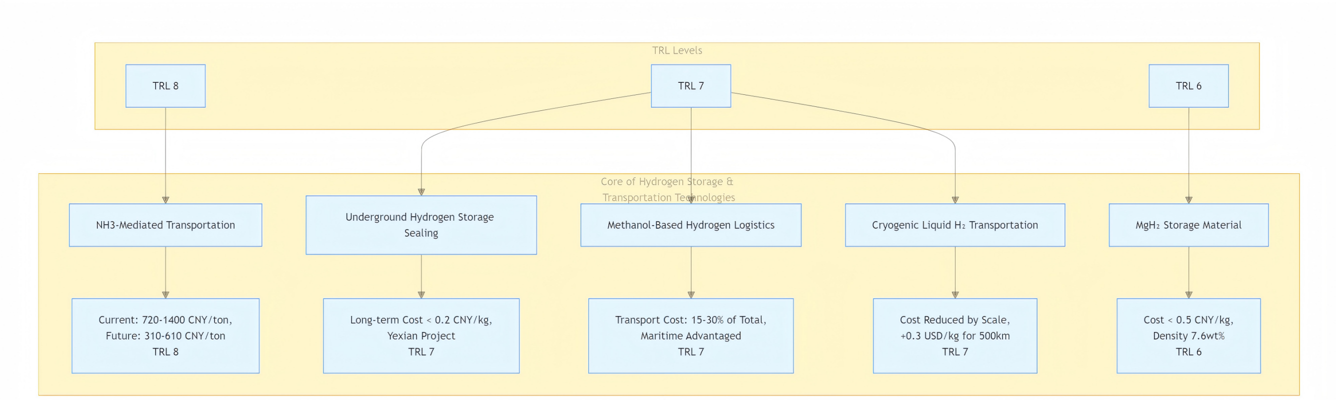

Figure 1 I Hydrogen Storage and Transportation Technologies Comparison by TRL

ANALYSIS OF HYDROGEN ENERGY PRODUCTION METHODS, STORAGE AND TRANSPORTATION TECHNOLOGY CHARACTERISTICS AND ECONOMIC BENEFITS

The team led by Lü Zhihui in Yulin, China, has achieved the large-scale production of magnesium hydride (MgH_2) hydrogen storage materials, reducing the cost of hydrogen storage and transportation by 25%. The magnesium-based solid-state hydrogen storage technology developed by this team boasts a hydrogen storage density of 7.6wt%, which is higher than that of traditional magnesium hydrides (the industry average is 6.5wt%). With the completion of the 10,000-tonne production line, the cost of magnesium hydride materials is expected to drop from 1,000 yuan/kg to 300 yuan/kg, and the corresponding unit hydrogen storage cost can be controlled below 0.5 yuan/kg, which is 58% lower than that of high-pressure gaseous hydrogen storage (1.2 yuan/kg).

Dr. Barbara Kutchko from the United States pioneered underground hydrogen storage sealing technology and developed a new type of cement-based sealing material, achieving a balance between safety and economy in hydrogen storage scenarios such as salt caverns and depleted oil and gas reservoirs [5]. Taking the Yexian Salt Cavern Hydrogen Storage Project in Henan, China as an example, the total investment of this project exceeds 70 million yuan. Although the initial investment is relatively high, it has excellent sealing performance (leakage rate < 0.1% per year), and the long-term unit hydrogen storage cost is lower than 0.2 yuan/kg, which is 83% lower than the short-term cost of high-pressure gaseous hydrogen storage (1.2 yuan/kg). It is suitable for large-scale and long-term hydrogen storage.

The team led by Charles Johnston from Australia conducted a systematic economic comparison of different hydrogen carriers (ammonia, methanol, and liquid hydrogen). The results show that ammonia is the most cost-effective transportation medium, with a cost of 0.56 USD/kg H_2. The specific comparative analysis is as **Figure 1**.

When discussing the storage and transportation of hydrogen energy, it is inevitable to involve hydrogen production methods. Currently, the mainstream hydro-

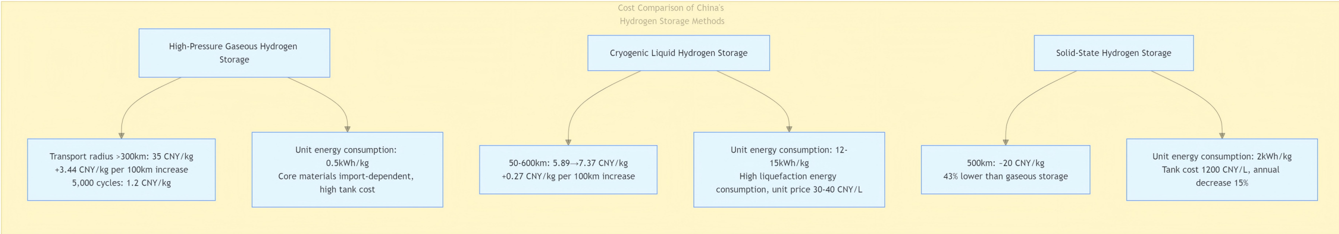

Figure 2 | Comparison of High-Pressure, Cryogenic & Solid-State Hydrogen Storage in China

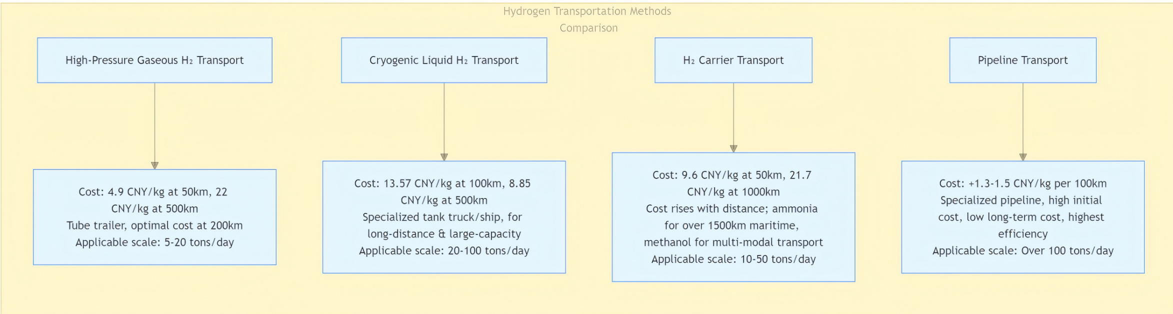

Figure 3 | Hydrogen Transportation Methods: Cost & Applicable Scale Comparison

gen production methods include hydrogen production through water electrolysis, hydrogen production from fossil fuels, biological hydrogen production, and hydrogen production through water photolysis. Among them, hydrogen production through water electrolysis is the core technical path of green hydrogen. After the price of alkaline electrolyzers drops by 38% year-on-year in 2025, the cost of hydrogen production through water electrolysis approaches 12 yuan per kilogram. If the carbon tax is taken into account (calculated based on the domestic carbon price of 50 yuan per ton), its cost is 20% lower than that of hydrogen production from fossil fuels (15 yuan per kilogram), and it has an economic advantage.

Hydrogen storage methods mainly fall into three categories: high-pressure gaseous hydrogen storage, cryogenic liquid hydrogen storage, and solid-state hydrogen storage. High-pressure gaseous hydrogen storage is currently the most mature and widely used method. Hydrogen storage in sealed pressure vessels has the advantages of simple equipment and fast hydrogen charging and discharging speed, while the disadvantages are low hydrogen storage density and large space occupation. The following FIG shows the cost comparison of the current three types of hydrogen storage methods in China (**Figure 2**).

There are mainly four types of transportation methods: high-pressure gaseous hydrogen transportation, cryogenic liquid hydrogen transportation, hydrogen carrier transportation, and pipeline transportation. The applicable scope and scenarios of various modes of transportation are supplemented as follows to clarify the technical boundaries (**Figure 3**).

RECOMMENDATIONS FOR HYDROGEN ENERGY AS A SUSTAINABLE ENERGY SOURCE IN STORAGE AND TRANSPORTATION

In response to the current challenges in hydrogen energy storage and transportation, such as high costs, technological bottlenecks, and insufficient industrial chain synergy, this section puts forward specific recommendations with clear priorities from a quantitative perspective by combining techno - economic analysis (TEA) and empirical data (e.g., the Yulin MgH_2 project and the Yexian Salt Cavern Hydrogen Storage Project in Henan Province), while supplementing solutions to non - technical barriers.

Enhance Cost Management: Reduce Costs Through Scale and Scenario - Adaptation

Priority should be given to reducing core costs through "raw material price locking and large - scale production". Drawing on the data from the 10,000 - ton production line of MgH_2 hydrogen storage materials developed by Lü Zhihui's team in Yulin, China, signing long - term agreements of more than 5 years with magnesium ore suppliers can reduce raw material procurement costs by 18%. Combined with the scale effect, the cost of MgH_2 materials can be reduced from 1,000 RMB/kg to 300 RMB/kg, driving the unit hydrogen storage cost to be less than 0.5 RMB/kg (Technology Readiness Level (TRL) 6, which means "laboratory verification completed and pilot production initiated") [5].

For the storage and transportation links, technologies should be adapted to specific scenarios:

Hydrogen Storage Side

Priority should be given to the use of reusable domestic carbon fiber hydrogen storage tanks. Currently, the proportion of domestic carbon fiber has increased to 35%, which is 22% lower than the cost of imported tanks. It is recommended to increase the domestic production rate to 60% by 2026 to further reduce the tank cost to 800 RMB/L.

Transportation Side

Promote 35MPa high - pressure transportation technology (currently at TRL 5, and pilot application at TRL 7 is expected to be realized in 2026) for short - distance (<300km, 5 - 20t/d) scenarios. Its unit cost is 20% lower than that of 20MPa technology (the cost for a 50km distance is reduced from 4.9 RMB/kg to 3.9 RMB/kg). For long - distance (>500km) scenarios, priority should be given to reusing existing infrastructure. For example, the "hydrogen - ammonia - methanol" project in Yantai, Shandong Province realizes cross - regional transportation through methanol maritime shipping (with a unit cost 15% lower than that of liquid hydrogen) [4].

Promote Technological Innovation: Focus on Breakthroughs in High - Maturity Technologies

Take technologies with "TRL 5+" as the core R&D direction to avoid wasting resources on low - maturity technologies:

Hydrogen Storage Materials

Focus on the research and development of composite metal hydrogen storage materials developed by Academician Li Can's team (hydrogen adsorption rate >8%, hydrogen desorption temperature 90°C, TRL 6). Through the synergistic optimization of nanonization and Ni - based catalysts, the goal is to reduce the hydrogen desorption temperature to 70°C and increase the hydrogen storage density to 9wt% by 2027, so that the cost of solid - state hydrogen storage tanks can be reduced by 15% annually (currently 1,200 RMB/L, with a target of 500 RMB/L by 2030) [2].

Transportation Monitoring

Promote the IoT + big data real - time monitoring system of Sinopec's "West - to - East Hydrogen Transmission" project. By deploying pressure and temperature sensors (sampling frequency once per minute), the equipment fault response time can be shortened from 2 hours to 15 minutes, and the maintenance cost can be reduced by 18%. This technology has passed TRL 7 verification (pilot application completed) [4].

Liquefaction Process

Optimize the liquefaction energy consumption of liquid hydrogen. Referring to the data of a liquefaction capacity of 150 tons per day, the application of new thermal insulation materials (vacuum multi - layer insulation layers) can reduce the liquefaction energy consumption from 12 - 15 kWh/kg to 8 kWh/kg, and the unit liquefaction cost from 1.2 RMB/kg to 0.8 RMB/kg [6].

Strengthen Industrial Chain Synergy: Break Through With Standards and Financing

Establish a Full - Chain Synergy Mechanism

Refer to the EU's HyDeal Ambition plan to build a closed loop of "hydrogen production - hydrogen storage - transportation - application":

Cost Synergy Through the integrated planning of "green hydrogen production + pipeline transportation", such as the Kubuqi Green Hydrogen Base in Inner Mongolia (with an annual production capacity of 200,000 tons), the pipeline transportation cost is 40% lower than that of the "hydrogen production + road transportation" mode (the cost for a 1,000km distance is reduced from 21.7 RMB/kg to 13 RMB/kg).

Standard Unification In accordance with the "Technical Requirements for Hydrogen Energy Storage and Transportation Systems" (T/CHEAA 002 - 2025) issued by the China Hydrogen Energy Alliance in 2025, clarify indicators such as hydrogen storage tank pressure levels (20MPa/35MPa) and transportation loss rate (≤0.5%/100km) to avoid adaptation costs caused by "standard fragmentation" [9].

Innovate Non - Technical Support Systems

Social Acceptance Carry out "hydrogen energy into communities" science popularization activities. Referring to the experience of Germany's "Hydrogen Dialog" project, by demonstrating the safety of salt cavern hydrogen storage (leakage rate <0.1%/year) on - site, the public acceptance of storage and transportation facilities can be increased from the current 52% to more than 70% [8].

Financing Model Issue national - level hydrogen energy special bonds. For example, the 10 billion yuan green bonds launched by the China Development Bank in 2025 focus on supporting Yexian - type salt cavern hydrogen storage projects (with a single project investment of 70 million yuan and a bond interest rate 1.2 percentage points lower than that of ordinary loans) to ease the capital pressure of heavy - asset projects [5].

Promote Green Development: Focus on Resource - Rich Areas and Low - Carbon Paths

Deploy green hydrogen projects in wind/solar resource - rich areas with "annual equivalent utilization hours >2,500h" (such as Inner Mongolia and Gansu). The hydrogen production cost here is 0.3 RMB/kWh lower than that in eastern regions. Combined with the integrated planning of "hydrogen production - pipeline", a closed loop of "green hydrogen production + low - carbon transportation" can be realized:

Case Reference

The Kubuqi Green Hydrogen Base in Inner Mongolia produces hydrogen through photovoltaics (cost 0.25 RMB/kWh) and combines it with a dedicated hydrogen pipeline (cost increases by 1.3 RMB/kg per 100km), controlling the green hydrogen delivery cost at 18 RMB/kg, which is more economical than fossil fuel - based hydrogen production (22 RMB/kg) [3].

Carbon Cost Optimization

Utilize the EU's Carbon Border Adjustment Mechanism (CBAM) (carbon price 80 Euros/ton). Through the "zero - carbon attribute" of green hydrogen storage and transportation, the carbon cost of export - oriented hydrogen - based steelmaking projects (such as the pilot project of Baowu Group) can be reduced by 50%, improving international competitiveness [4].

CONCLUSION

This study adopts a techno - economic comparative analysis method. Based on global and Chinese empirical data on hydrogen energy storage and transportation (global hydrogen demand reached 97 million tons in 2023, and the scale of green hydrogen projects in China reached 620 MW in 2025), it quantitatively analyzes the costs and performances of high - pressure gaseous, cryogenic liquid, magnesium - based solid - state hydrogen storage, and ammonia/methanol carrier transportation. The core conclusions are as follows:

Technology - Scenario Adaptability

For short - distance (<200km, 5 - 20t/d) scenarios, high - pressure gaseous transportation is preferred (cost 4.9 - 22 RMB/kg); for long - distance (>500km, 20 - 100t/d) scenarios, cryogenic liquid hydrogen (cost 8.85 RMB/kg for 500km) or ammonia carriers (maritime shipping cost 0.56 USD/kg H_2 for 1,500 - 3,500km) are more suitable; solid - state hydrogen storage has significant advantages in medium - short distance (200 - 500km) scenarios (cost 20 RMB/kg, 43% lower than high - pressure gaseous storage) [2, 6].

Cost Reduction Path

Through "large - scale production (70% cost reduction of MgH_2 10,000 - ton production line) + technological innovation (liquefaction energy consumption reduced to 8 kWh/kg) + industrial chain synergy (40% cost reduction through pipeline reuse)", the levelized cost of green hydrogen (LCOH) can be reduced from the current 15 RMB/kg to below 10 RMB/kg by 2030, meeting the economic needs of industrial decarbonization (such as hydrogen - based steelmaking) [3, 9].

Key Breakthroughs in Non - Technical Aspects

Social acceptance (improvement of public awareness) and innovative financing (support from special bonds) are important supports for the implementation of storage and transportation technologies, and need to be promoted simultaneously with technology R&D to avoid "technically feasible but difficult to implement" [5, 8].

The limitation of this study is that it does not cover the storage and transportation costs under extreme low temperatures (<-30°C). In the future, research can focus on the development of low - temperature solid - state hydrogen storage materials (such as new composite metals with hydrogen adsorption rate >10%) to further expand the application scenarios of hydrogen energy. Countries around the world need to strengthen technical cooperation (such as the linkage between China - Europe "West - to - East Hydrogen Transmission and HyDeal") to accelerate the standardization and scale - up of hydrogen energy storage and transportation, and contribute to the realization of the global "carbon neutrality" goal.

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