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Short Communication

Impact of metal-based hydrogen production on the hydrogen energy industry chain

Xiangyu Meng[a], Qian Sun[b], Jinxiao Wang[c], Alun Gu[d,*], Jian Zhou[d], Bin Liu[d], Zongqiang Mao[e,*]

[a] Guangdong Tsingda Innovation Research Institute, Dongguan, 523808, China
[b] School of Economics and Management, Tsinghua University, Beijing, 100084, China
[c] CNOOC Energy Economics Institute, Beijing, 100013, China
[d] Institute of Energy, Environment and Economy, Tsinghua University, Beijing, 100084, China
[e] Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing, 100084, China

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ABSTRACT

Metal-steam thermochemical hydrogen production technology (referred to as metal-based hydrogen production) utilizes the reaction between metals and steam to efficiently produce green hydrogen, offering advantages such as convenient hydrogen production, mild production conditions, abundant metal raw materials, low transportation costs, and high safety. This paper systematically analyzes the disruptive impact of this technology on the four segments of the hydrogen energy industry chain—"production-storage-transportation-utilization"—and explores its advantages in terms of cost, safety, and reliability. Research indicates that metal-based hydrogen production technology is expected to reshape the structure of the hydrogen energy industry chain, significantly reduce the cost of hydrogen use, and provide key technical support for the large-scale application of hydrogen energy and the achievement of carbon neutrality goals. It is projected that by 2030, the cost of metal-based hydrogen production will drop below $2.19/kg, making it competitive with renewable energy electrolysis for water splitting.

1. Introduction

The hydrogen energy industry chain is increasingly recognized as a critical component of the global transition to a sustainable and low-carbon energy system. Despite its significant potential, the widespread adoption of hydrogen faces substantial challenges across production, storage, transportation, and downstream application segments (China National Alliance of Hydrogen and Full Cell, 2023; National Development and Reform Commission and National Energy Administration, 2022;).

In the area of hydrogen production, a primary concern is the limited capacity for clean hydrogen generation. Conventional methods, such as natural gas reforming and coal gasification, remain economically advantageous but are associated with considerable carbon emissions, posing a direct conflict with international decarbonization objectives. Alternatively, renewable hydrogen—produced mainly through water electrolysis—is hindered by high capital and operational expenditures. Moreover, the variable nature of renewable power sources introduces additional technical demands for flexible and responsive electrolyzer operation. Recent techno-economic optimization of photovoltaic-electrolyzer systems highlights that dynamic operation and capacity coupling enable substantial reductions in levelized cost of green hydrogen (Lee et al., 2024); demonstrate, through multi-objective optimization under stochastic irradiance, that hybrid storage (battery + hydrogen) enhances system flexibility and improves annual hydrogen yield by up to 18% compared to rigid grid-connected designs. Such integrated approaches are essential to accelerate cost-competitive renewable hydrogen beyond conventional water electrolysis paradigms.

The storage and transportation of hydrogen present another set of critical barriers. Geographical disparities between regions capable of large-scale green hydrogen production and centers of demand necessitate long-distance transport, leading to complex logistics and elevated costs. While high-pressure gaseous hydrogen storage is a mature technology, its low volumetric density and inherent safety risks remain unresolved. Emerging alternatives, such as liquid hydrogen and solid-state storage approaches, are still in nascent stages of development, grappling with technical limitations and high costs. In this context, data-driven and advanced material breakthroughs offer promising pathways

* Corresponding authors.
E-mail addresses: gal@mail.tsinghua.edu.cn (A. Gu), maozq@mail.tsinghua.edu.cn (Z. Mao).

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(Rahimi et al., 2021) employed machine learning models (support vector machines optimized via genetic algorithms) to predict hydrogen adsorption on porous bio-derived activated carbons, achieving a 2.5wt% uptake improvement by tailoring micropore surface area and pore size distribution — a systematic guide for next-generation physisorption media. In Parallel, Moreno and García (2024)conducted a similar study. synthesized a novel MOF-5 composite for hydrogen purification via pressure swing adsorption; the material exhibits enhanced H_2/CO_2 selectivity (above 38 at 298 K) and facilitates high-purity hydrogen recovery (≥99.97%), which directly addresses impurity accumulation during long-distance transport and storage cycles. Compounding these issues, the slow rollout of essential infrastructure, including hydrogen refueling stations, further restricts commercial scalability.

At the downstream application level, market uptake remains sluggish. Although hydrogen holds promise in decarbonizing sectors such as transportation and industry, current market awareness and acceptance are limited. This lack of robust demand-side pull continues to impede investment and scale-up across the entire value chain. Additionally, impurity control directly influences end-use device durability: the advanced adsorbents developed by Moreno and García (2024) not only improve storage purity but also mitigate catalyst poisoning in PEM fuel cells, demonstrating that integrated purification-storage systems are critical for reliable downstream conversion. Moreover, life-cycle assessments incorporating dynamic production profiles (Lee et al., 2024) confirm that green hydrogen costs can approach parity with grey hydrogen when sector-coupling and flexible operation are prioritized — a key driver for demand creation in industrial heating and heavy mobility.

Given these multifaceted challenges, advancing the hydrogen economy will require coordinated efforts in technological innovation and supportive policy frameworks. This paper examines these persistent bottlenecks and explores potential pathways to overcome them, with the aim of supporting the sustainable development of the hydrogen industry.

2. Principles and development status of metal thermochemical hydrogen production technology

2.1. Technical principles

Metal-steam thermochemical hydrogen production is a branch of thermochemical hydrogen production technology, which utilizes the chemical reaction between metals and steam at high temperatures to produce hydrogen. Commonly used metals in this process include aluminum, zinc, magnesium, and iron. As early as the 1940s, the United States began researching hydrogen production from metal-water reactions (US Department of Energy, 2023).

Taking the high-temperature reaction of metallic aluminum with steam to produce hydrogen as an example, depending on the reaction temperature, the aluminum-water reaction involves the following two specific reactions:

$$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2$$

$$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2$$

This reaction faces challenges both in terms of economic cost and technology. During the reaction, an $Al(OH)_3$ film forms on the surface of Al, hindering the occurrence of the metal aluminum hydrolysis reaction. Removing surface oxides and inhibiting the formation of the oxide film are the focus of related research. Methods to remove the $Al(OH)_3$ film mainly include the following: (1) Increasing the temperature during the reaction process; (2) Enhancing the metal's oxidation resistance by synthesizing alloys; (3) Promoting the reaction by doping with metal salts or metal oxides; (4) Carrying out the reaction under strong alkaline conditions to break the oxide film during the process; (5) In-situ regeneration.

However, even if the relevant technical limitations are broken through to achieve the ultimate hydrogen production ratio (9 kg of aluminum producing 1 kg of hydrogen), the hydrogen production ratio is still very limited, and the hydrogen production process faces very high costs, unable to meet commercial requirements.

2.2. Technological breakthroughs and development status

Industry is actively committed to developing new hydrogen production cracking agents to solve the technical problems of single-metal hydrogen production, such as surface oxide film formation, small contact area, uncontrollably fast reaction, and the high economic cost caused by low hydrogen production ratio.

Taizhou Zhonghe Hydrogen Energy Technology Co., Ltd. uses common metals and alloys such as ferrocene, aluminum, metal chlorides, molybdenum, manganese, potassium, calcium, tin, zinc, and magnesium as core components to develop cracking agents (Taizhou Zhonghe Hydrogen Energy Technology Co., Ltd., 2023). When applied to the hydrogen production process, these agents can reduce the oxide film formed during hydrogen production and increase the contact area through binders or mesoporous silica, resulting in a stable and controllable reaction and a significant increase in the hydrogen production ratio. Third-party testing and analysis results show that 25 g of metal sample can stably produce 360.29 g of hydrogen, with a hydrogen production ratio nearly 130 times that of conventional aluminum-water hydrogen production. The hydrogen purity produced by applying this cracking agent in the hydrogen production process is greater than 94.44%, with water vapor at 5.55% (ZHONGHE Hydrogen, 2023).

Jiangsu Zhongxi Hydrogen Energy Technology Co., Ltd. designed and manufactured a metal cracking steam green hydrogen production device with a hydrogen production capacity of 500 cubic meters per hour for Shandong Feicheng Ruifu Lithium Industry. Utilizing waste heat from the rotary kiln, low-grade steam (160°C) produced by the evaporator enters the reaction tank to react with the metal catalyst and decompose to produce hydrogen, realizing the efficient utilization and integrated development of hydrogen energy in the lithium battery industry (Jiangsu Zhongxi Hydrogen Energy Technology Co.Ltd, 2024).

A comparative summary of recently reported metal-based hydrogen production technologies (including the breakthroughs above and other notable systems) is provided in Table 1.

These technological breakthroughs indicate that metal thermochemical hydrogen production technology is gradually moving from the laboratory to industrial application, providing a practical and feasible technical path to solve the pain points in the hydrogen energy industry chain.

2.3. Technical barriers and economic limitations

The primary techno-economic barrier for metal-based hydrogen production lies in the short lifespan of the metal cracking agent, requiring monthly replacement. This can be addressed by enhancing hydrogen yield per unit mass, extending replacement intervals from one month to three months, with the prospect of annual replacement. Competitiveness remains limited due to high costs, lack of scale, and insufficient policy support. Key improvements include: (1) standardized modular designs to reduce manufacturing and operational costs; (2) full-chain cost reduction through recycling, scaling, and integration with renewable energy or waste heat; and (3) enabling policies such as safety codes, non-chemical-park deployment permissions, and carbon pricing or subsidies. Collectively, these measures can significantly enhance the techno-economic viability of metal-based hydrogen production.

Table 1
Comparative summary of metal-based hydrogen production technologies from recent literature.

Study/technology	Metal system	H_2 yield (g/g metal)	Reaction temp. (°C)	H_2 purity (%)	LCOH ($/kg)	Key innovation
Taizhou Zhonghe Hydrogen Energy Technology Co.Ltd (2023)	Fe/Al/Mo/Mn multi-component	14.4 (360 g H_2/25g agent)	160	94.4	1.58	Mesoporous silica binder, 130× improvement
Meng et al. (2023)	Al-11%Ga-3%In-1%Sn	13.5	25-85	>98	9.2	Room temp. activation, Ea = 18.22 kJ/mol
Kombargi et al. (2025)	Recycled Al + eGaIn	11.1	25-100	>99	9.2	Closed-loop Ga-In recovery, 1.45 kg CO_2eq/kg H_2
Jiangsu Zhongxi Hydrogen Energy Technology Co.Ltd (2024)	Composite cracking agent	12.5 (industrial scale)	160	95	1.2	Waste heat integration, 500 Nm^3/h unit
Woodall alloy (2008)	Al-5%Ga-In-Sn	9.0 (theoretical)	25-90	>99	10.0	Two-phase solid alloy, reusable Ga
Wang et al. (2009)	Pure Al powder	1	>80	99	>20	Baseline technology

3. Reshaping of the industry chain structure by metal-based hydrogen production

3.1. Subversion of the traditional industry chain sequence

The traditional hydrogen energy industry chain follows the model of "produce hydrogen first, then transport hydrogen", i.e., centralized production of green hydrogen in areas rich in green electricity resources such as hydropower, wind power, and photovoltaics, followed by transportation to consumption ends via high-pressure gaseous or liquid methods. This model faces challenges such as hydrogen being light in weight but large in volume, difficult and costly to store and transport.

Metal-steam hydrogen production technology completely subverts this traditional model, transforming it into a new paradigm of "transport metal first, then produce hydrogen locally". Specifically, high-energy-density metals (such as aluminum, magnesium, zinc, etc.) or composite cracking agents are transported to the hydrogen usage terminal, where hydrogen is produced on-site by introducing 160-300°C low-grade steam. This model eliminates high-pressure storage tanks and long-tube trailers, enhancing the intrinsic safety level by an order of magnitude. A comparison between the traditional hydrogen energy industry chain and the metal-based hydrogen production industry chain is shown in Fig. 1.

The significance of this change lies not only in the alteration of the technical route but also in the reconstruction of the value chain of the hydrogen energy industry. Metals, as solid materials, have far higher safety and economic efficiency in transportation and storage than hydrogen, making large-scale application of hydrogen energy more feasible.

3.2. Significant reduction in storage and transportation costs

The volumetric hydrogen storage density of metals/cracking agents reaches 60-110 kg-H_2/m^3, which is 4-6 times that of 70 MPa high-pressure hydrogen storage cylinders. This characteristic gives metals a clear advantage in hydrogen storage. More importantly, metals can be transported as ordinary solid materials, by rail or road, classified as ordinary solid waste/hazardous goods, greatly reducing transportation difficulty and cost.

Calculations show that the terminal delivery cost for metal transported over 1000 km is only 0.084-0.113 $/kg-$H_2$, while the cost for liquid hydrogen transportation is about $0.36/kg-$H_2$, and the cost for high-pressure gaseous hydrogen transportation is even higher. Overall, the storage and transportation cost of metal-steam hydrogen production is 50%-70% lower than traditional methods, which is of great significance for alleviating the "hydrogen shortage" problem between Northwest and Southeast China.

This cost advantage is a disruptive alternative to the hydrogen energy pattern of "West-to-East Hydrogen Transport" and "North-to-South Hydrogen Transport." In the traditional model, hydrogen transportation costs account for a relatively high proportion of the total cost and increase significantly with transportation distance. The metal-based hydrogen production model drastically reduces transportation costs and is less sensitive to transportation distance, which helps optimize the spatial layout of the hydrogen energy industry.

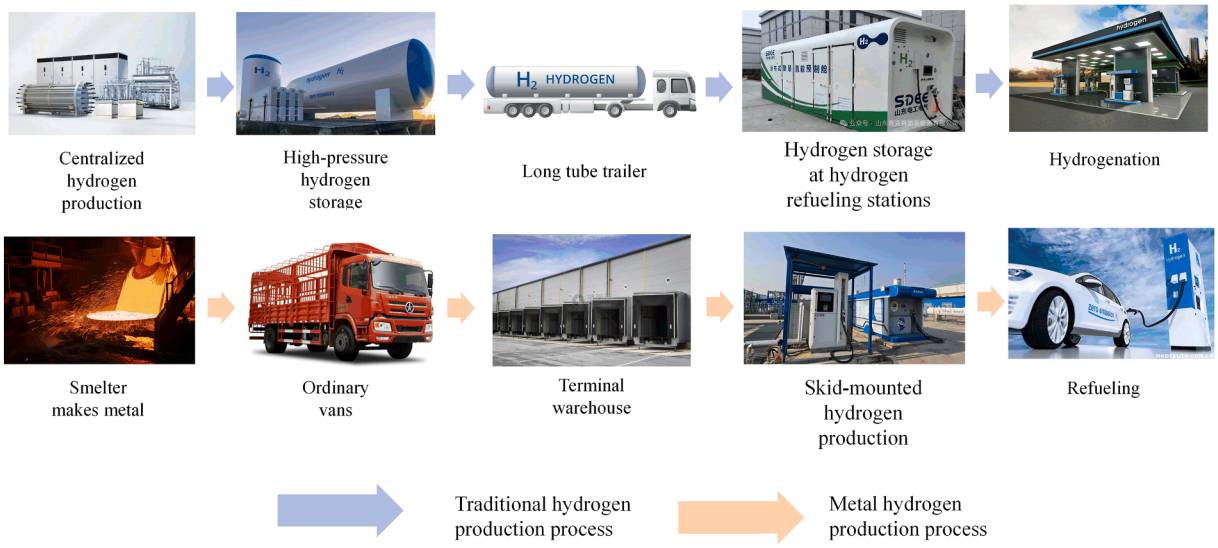


Fig. 1. Schematic illustration of the composition and comparison between the conventional hydrogen energy industry chain and the metal-based hydrogen production industry chain.

Life cycle assessment (LCA) elucidates the critical role of transportation in the overall carbon footprint of hydrogen supply chains. Conventional transport modes incur substantial emissions: high-pressure gaseous hydrogen delivered via tube trailers contributes 0.5–2.0 kg CO_2eq per kilogram of hydrogen per 1000 km, primarily due to diesel combustion and compression energy, while liquid hydrogen transport results in 1.5–3.0 kg CO_2eq/kg H_2/1000 km, accounting for energy-intensive liquefaction (10–12 kWh/kg) and boil-off losses. In stark contrast, metal-based hydrogen carriers, such as aluminum or cracking agents, are transported as ordinary solid goods, yielding only 0.05–0.15 kg CO_2eq/kg H_2/1000 km via rail or road logistics. Consequently, transportation accounts for less than 5% of total life cycle emissions in metal-based systems, compared to 15%–25% for compressed or liquid hydrogen pathways. At the system level, optimized aluminum–seawater configurations with recycled aluminum achieve a carbon intensity of 1.45 kg CO_2eq/kg H_2, positioning this route competitively against renewable electrolysis (1.5–3.0 kg CO_2eq/kg H_2) and markedly below steam methane reforming (10–12 kg CO_2eq/kg H_2).

3.3. Lowering the threshold for terminal hydrogen refueling

The promotion and application of metal-steam hydrogen production technology significantly lower the investment and operational thresholds for terminal hydrogen refueling stations. A 350 Nm^3/h skid-mounted unit occupies only 18 m^2, requires no external power grid connection, can utilize existing steam or waste heat at the refueling station, and the CAPEX (Capital Expenditure) for a single unit has been reduced to $1.17–1.46 million, equivalent to 45% of electrolysis equipment of the same scale, and saves the 30 MPa high-pressure hydrogen storage cylinder group.

These technical characteristics make the skid-mounted "refueling station" model possible, similar to traditional gasoline and diesel stations, allowing flexible layout in various urban areas and greatly improving the convenience of hydrogen use. Starting in 2025, pilot projects for "integrated hydrogen production and refueling stations" exempt from permits have been launched in Shandong, Sichuan, and other places, reducing the approval cycle from 18 months to 6 months, further accelerating the commercial application of metal-based hydrogen production technology.

The reduction in investment threshold for hydrogen refueling stations and the simplification of approval processes will greatly promote the construction of hydrogen energy infrastructure, creating favorable conditions for the popularization of hydrogen vehicles. It is predicted that by 2030, the number of hydrogen refueling stations in China is expected to reach over 5000, with a considerable portion adopting metal-based hydrogen production technology.

4. Economic viability and application expansion of metal-based hydrogen production

4.1. Expanding distributed hydrogen usage scenarios

Metal-steam hydrogen production technology provides a new distributed hydrogen usage scenario of "hydrogen-steam co-supply" for the industrial sector. The complete technical process is shown in Fig. 2.

As shown in Fig. 2, low-pressure steam users such as textiles, food, and pharmaceutical factories can add a metal cracking module at the tail of the boiler, reinjecting 3%-8% hydrogen into the furnace for mixed combustion, achieving 18%-25% natural gas savings, 40%-50% reduction in NO_x emissions, and simultaneously shortening the investment payback period.

This model means "hydrogen consumption" no longer relies solely on the single outlet of fuel cell vehicles, providing millions of tons of decentralized demand for hydrogen energy. Especially in the industrial sector, hydrogen energy can serve as a clean fuel and reducing agent, replacing traditional fossil fuels and achieving deep emission reductions.

4.2. Providing a new path for green hydrogen cost reduction

The cost of metal cracking agents currently accounts for 60% of the Levelized Cost of Hydrogen (LCOH). With the expansion of green power aluminum and green power magnesium in the metallurgical industry,

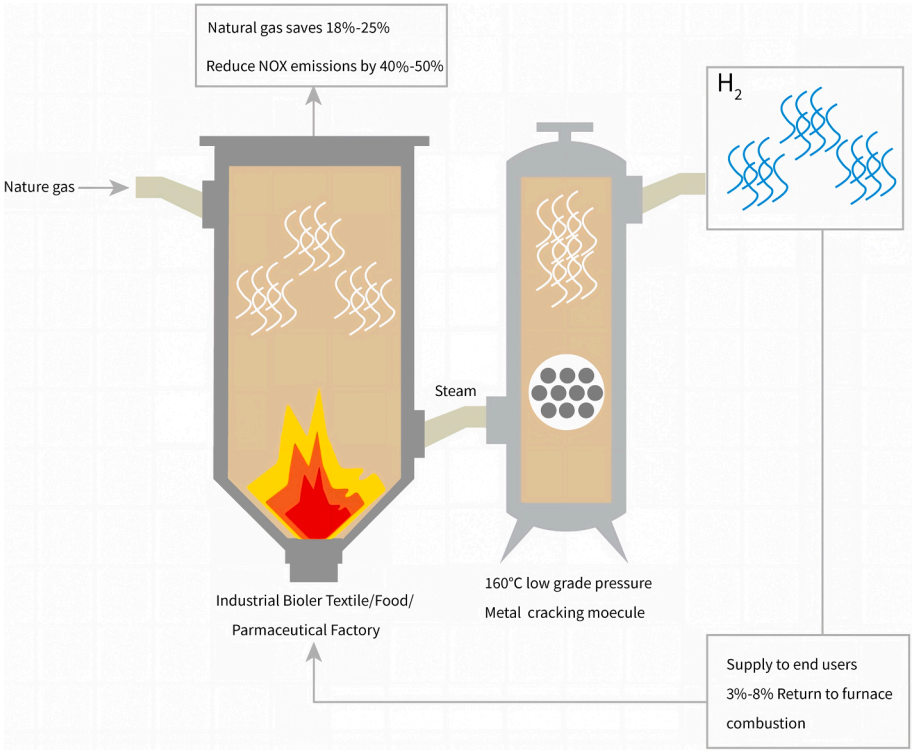


Fig. 2. Schematic illustration of the process for hydrogen production and steam co-supply.

the price of cracking agents could drop by 40%. Coupled with the potential for free utilization of 160°C saturated steam waste heat, the comprehensive cost of metal-steam hydrogen production is expected to drop below $2.19/kg during 2027-2030, on par with the cost of renewable electrolysis during off-peak electricity prices of $0.022/kWh. The cost reduction trends under different scenarios are shown in Fig. 3.

This cost reduction path provides a "second channel" for green hydrogen development, different from the electrolysis path that relies on electricity price reductions. The cost reduction of metal-based hydrogen production mainly comes from raw material cost reduction and technological progress, complementing the cost reduction mechanism of electrolysis.

Quantitative modeling projects the levelized cost of hydrogen (LCOH) for metal-based systems to fall below $2.08/kg by 2030 through targeted reductions across three components. Cracking agent costs, currently 61% of total, are expected to decline by 40%–50% via green aluminum and high-efficiency recovery of activation metals. Steam costs, accounting for 30%, can be largely eliminated through industrial waste heat integration. Equipment costs benefit from learning rates and modular production. These combined effects yield a projected LCOH of $0.77/kg, with byproduct credits further lowering the net cost to $1.90–2.00/kg, achieving parity with renewable electrolysis, SMR with carbon capture, and European green hydrogen targets for 2030.

4.3. Driving upstream green metallurgy development

The development of metal-steam hydrogen production technology will create new pull for the upstream metallurgical industry and the circular economy. Based on a scale of 1 million tons of hydrogen, it would consume approximately 3 million tons of aluminum or 4.5 million tons of magnesium, corresponding to a green metallurgy market of $8.75 billion. The by-products, alumina and magnesia, can directly enter the building materials and flame retardant material chains, realizing a "metal-hydrogen-material" triangular cycle and providing additional revenue channels for the carbon neutrality of the steel and nonferrous metal industries.

This synergistic effect of the industry chain makes metal-based hydrogen production not only an energy technology but also a bridge connecting the energy and materials fields. Through the circular utilization of metal-hydrogen-materials, resource utilization can be maximized and carbon emissions minimized, aligning with the concept of a circular economy.

It is particularly noteworthy that the metal oxides produced as by-products of metal-based hydrogen production have high economic value and can be used as building materials, flame retardants, etc. (as shown in Fig. 4). The value of by-products can offset part of the hydrogen production cost, making the overall economics more favorable.

5. Techno-economic analysis of metal-based hydrogen production technology

5.1. Cost composition analysis

The cost of metal thermochemical hydrogen production is the core factor determining whether it can achieve effective industrial promotion. Table 2 shows the current cost composition of metal-steam thermochemical hydrogen production.

As can be seen from Table 1, the cost of the metal cracking agent accounts for 61% of the total cost and is the main factor affecting the hydrogen production cost. Steam cost accounts for 30%, and equipment depreciation and labor costs account for 9%. This cost structure indicates that the room for cost reduction in metal-based hydrogen production lies mainly in the reduction of the cracking agent cost.

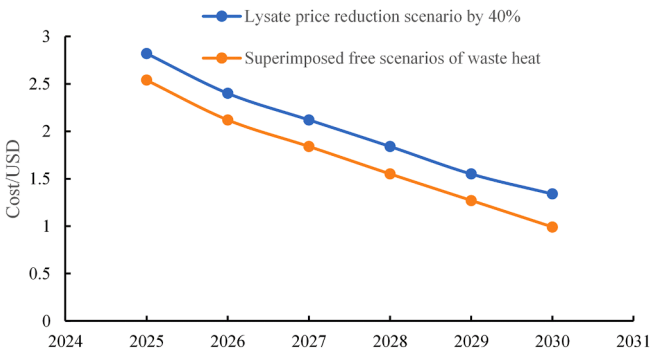


Fig. 3. Cost reduction trends under different scenarios.

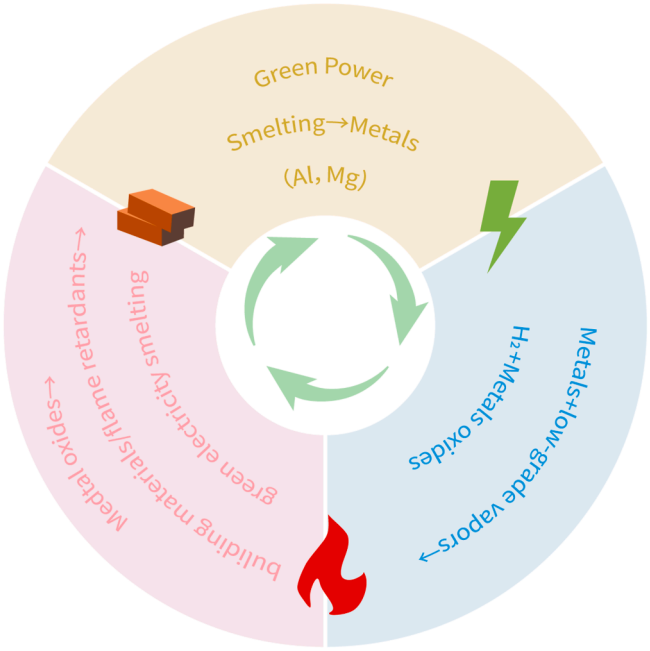


Fig. 4. Schematic diagram of the Metal-Hydrogen-Material triangular cycle.

Table 2
Cost composition of metal-steam hydrogen production (Unit: $/kg H2).

Item	Unit price	Cost ($)/Proportion %
Metal Cracking Agent	14.00 $/kg	0.97/61
Steam	36.40 $/ton	0.47/30
Equipment Depreciation & Labor	–	0.14/9
Subtotal	–	1.58/100

Data source: Estimated based on industry survey data (Taizhou Zhonghe Hydrogen Energy Technology Co., Ltd. ,2023).

5.2. Cost comparison with other hydrogen production methods

A comparison of the total costs of hydrogen energy industry chains constituted by different hydrogen production technologies is shown in Fig. 5.

From Fig. 5, it can be seen that although the total cost of coal-based hydrogen production is the lowest, its production process is accompanied by large amounts of greenhouse gas emissions. Among various clean hydrogen production processes, metal-steam hydrogen production shows a clear advantage in total cost. It is particularly noteworthy that the transportation cost accounts for a large proportion of the total cost in different hydrogen production-storage-transportation processes, while the transportation cost of metal-steam hydrogen production is mainly

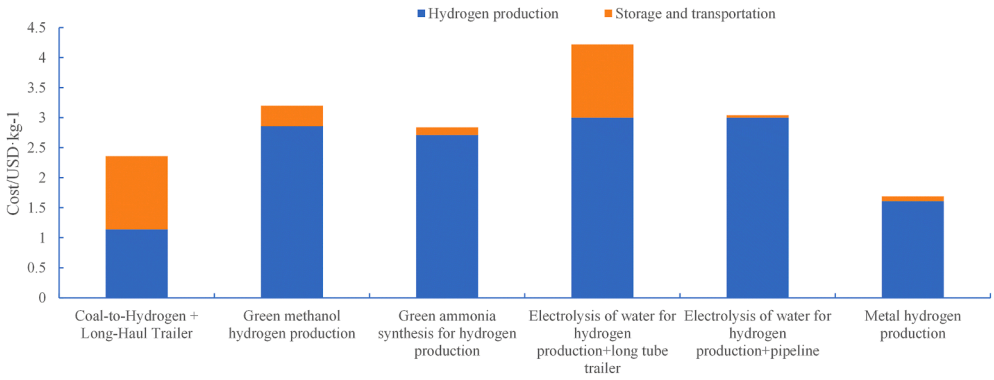


Fig. 5. Cost comparison of different hydrogen production technology routes.

concentrated on the transportation of aluminum metal, which is the lowest. Comprehensive analysis shows that the metal-steam hydrogen production method has a greater cost advantage.

5.3. *Analysis of cost reduction potential*

Metal-based hydrogen production technology has significant cost reduction potential, mainly reflected in the following aspects:

First, the cost of metal cracking agents is expected to decrease significantly. Currently, cracking agent costs account for 61% of the total hydrogen production cost. With scaled production and technological progress, the price of cracking agents is expected to drop by more than 40%. In particular, the development of green metallurgy technologies such as green power aluminum and green power magnesium will further reduce cracking agent costs.

Second, there is considerable room for optimization of steam costs. Metal-based hydrogen production can use low-grade steam (above 160°C), which is widely available in industrial production and is often wasted as waste heat. By fully utilizing industrial waste heat, steam costs can be significantly reduced.

Third, equipment costs decrease with scaled production. Currently, metal-based hydrogen production equipment is still in the demonstration stage, with high production costs. As the industrialization scale expands, equipment costs are expected to drop by more than 30%.

Considering these factors comprehensively, it is estimated that by 2030, the cost of metal-steam hydrogen production will drop below 15 yuan/kg, comparable to the cost of renewable energy electrolysis for hydrogen production, making it market competitive.

5.4. *Quantitative safety assessment*

Quantitative safety assessment substantiates that the metal–steam system enhances intrinsic safety by more than an order of magnitude relative to 70 MPa compressed hydrogen. The compressed hydrogen configuration poses substantial hazards: catastrophic rupture releases stored mechanical energy of 15.9 MJ L^{-1}, equivalent to 3.8 kg TNT per kg H_2, combined with an extremely low minimum ignition energy (0.02 mJ) and broad flammability range (4vol%–75vol%). In contrast, the metal–steam system operates at ambient pressure (0.1–0.5 MPa), eliminating stored mechanical energy and high-pressure risks. Quantitative metrics reveal reductions in operating pressure by a factor of 140–700, stored mechanical energy by over 100-fold, and theoretical explosion overpressure by 20–40-fold. Moreover, the steam atmosphere intrinsically suppresses ignition probability. These improvements collectively demonstrate a paradigm shift from high-pressure physical storage to low-pressure chemical storage, confirming superior intrinsic safety for stationary and safety-critical applications.

6. Conclusions

In summary, metal-steam hydrogen production technology demonstrates unique advantages in safety, economic viability, and industry chain compatibility, possessing the strategic potential to become a “second channel” for China's green hydrogen supply. This technology transforms hydrogen energy from “high-pressure + high-risk + long-distance transport” to “ambient temperature and pressure solid storage and transport + local low-pressure hydrogen production”. Its commercial significance lies not only in reducing terminal costs by 20%-30% but also, for the first time, freeing hydrogen energy from the “long-tube trailer bottleneck”, forming a supply chain as convenient as diesel and natural gas. It is a key springboard for hydrogen energy to move from demonstration to scale.

CRediT authorship contribution statement

Xiangyu Meng: Investigation, Methodology, Project administration, Writing – original draft. **Qian Sun:** Formal analysis, Resources, Software, Validation. **Jinxiao Wang:** Resources, Validation. **Alun Gu:** Formal analysis, Funding acquisition, Resources. **Jian Zhou:** Investigation, Methodology, Visualization. **Bin Liu:** Supervision, Validation. **Zongqiang Mao:** Conceptualization, Data curation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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