Technology Review for Carbon Neutrality

Perspective

A three-stage roadmap and key issue outlook for China's hydrogen energy industry toward 2060

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ABSTRACT

China has recently elevated hydrogen energy to a strategic priority within its national energy security framework. As policy support, technology maturation, and regulatory integration advance, the sector is moving from preliminary demonstration toward more systematic deployment. This study develops a three-stage roadmap for China's hydrogen energy industry toward 2060 by integrating techno-economic modeling, scenario analysis, and policy-target cross-checking. The results suggest a staged evolution within the broader energy system: scenario-specific enablement through 2030, system regulation and cross-sector integration during 2030–2040, and a possible foundational energy-carrier role by 2060. In the current phase, hydrogen deployment is constrained by high renewable-hydrogen costs, incomplete safety regulation, and system-compatibility barriers; its role therefore remains concentrated in selected industrial and mobility applications. In the mid-term phase, declining renewable-hydrogen costs and maturing storage and transportation networks could allow hydrogen to support long-duration energy storage, renewable-power integration, and industrial decarbonization. In the long term, hydrogen may form a dual-carrier energy architecture with electricity, provided that technology, safety governance, infrastructure, and standards continue to mature. The proposed roadmap offers a structured reference for hydrogen-related policy planning, infrastructure investment, and future research under China's carbon-neutrality transition.

KEYWORDS

Hydrogen energy industry; low-carbon energy transition; industry roadmap; techno-economic modeling; green hydrogen; China

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1. Introduction

China aims for non-fossil energy to account for more than 80% of energy consumption by 2060[1]. However, the inherent volatility and intermittency of renewable energy make it challenging to precisely match with electricity load demands, and large-scale integration still faces significant technical and systemic barriers[2,3]. Hydrogen energy, as a clean secondary energy source with diverse origins and zero emissions at the point of use, offers a key pathway to address this challenge. Through water electrolysis technology, fluctuating renewable energy sources such as wind and solar power can be converted into stable hydrogen energy and its derivatives. Leveraging cross-regional dispatch networks and cross-energy-source coupling technologies, this approach effectively enhances renewable energy integration capacity, providing crucial support for building new power systems and achieving a green energy transition[4-6].

After more than two decades of development, China's hydrogen energy industry has completed its pilot exploration phase. By the end of the 14th Five-Year Plan period, it had entered a new phase of orderly breakthroughs[7]. However, constrained by hydrogen's flammable and explosive physical properties, it has long been classified under hazardous chemical management and must comply with stringent regulatory requirements for hazardous chemicals[8]. This has to some extent limited the industry's development space, resulting in hydrogen currently playing only a limited role in scenarios such as partially replacing high-carbon raw materials in industrial processes and demonstrating clean transportation in the mobility sector. The Energy Law of the People's Republic of China, effective January 1, 2025, explicitly classifies hydrogen as an energy source, formally establishing its energy attributes at the legal level[9]. This institutional breakthrough provides crucial support for the hydrogen industry to break development constraints and achieve a transformative leap in its role.

Existing research has examined several core dimensions of China's hydrogen energy industry, including technological pathways, medium- and long-term supply-demand dynamics, application scenarios, and international experiences[10-13]. These studies provide important references for understanding hydrogen production technologies, sectoral demand, and policy pathways. However, many of them focus on a single dimension, such as technology review, scenario simulation, policy analysis, or application diversification, and therefore provide limited explanation of how hydrogen's system role may evolve over time.

Compared with these studies, the novelty of this work lies in three aspects. First, it links hydrogen supply, consumption, cost trajectories, infrastructure constraints, safety governance, and standards into one integrated three-stage roadmap. Second, the stage boundaries are not defined only by policy milestones; they are also cross-checked against modeled changes in cost competitiveness, storage and transportation coverage, and system-integration capability. Third, the paper interprets hydrogen's evolving function from scenario enablement to system regulation and then to a foundational energy-carrier role, thereby connecting techno-economic projections with energy-system transformation and policy planning toward 2060.

ABI Research projects that global green hydrogen production costs could fall to approximately $1.80/kg (about 13 yuan/kg) by 2040[14]. Separately, the International Energy Agency suggests that renewable hydrogen in China could become cost-competitive with unabated fossil-based hydrogen by 2030, owing to low technology costs and a low cost of capital[16]. In our China-focused analysis, green hydrogen production costs could fall below 10 yuan/kg by 2040 under favorable learning-curve and renewable-electricity scenarios. This projection reflects China's large electrolyzer manufacturing capacity, lower equipment costs, and rapid renewable-energy deployment. The timing remains sensitive to electricity prices, utilization rates, and infrastructure costs[15,16].

2. Modeling analysis performed

In our techno-economic study, we forecast China's future hydrogen supply-system scale, consumption-system scale, and green hydrogen costs (Figs. 1–3). To improve the traceability of the quantitative projections, the numerical values used in this study are classified into three groups: historical baseline data for 2020–2024, which are drawn from the National Bureau of Statistics, industry yearbooks, and cited sectoral reports; policy and literature benchmarks, which are used to define milestone constraints and to cross-check the plausibility of the results; and scenario-based projections for 2025–2060, which are generated by the integrated modeling framework. Unless otherwise specified, the forward-looking figures on hydrogen supply, demand, sectoral shares, storage and transportation scale, and green hydrogen costs should therefore be interpreted as model-based scenario outputs rather than fixed policy targets.

The modeling workflow proceeds in four steps. First, historical production, consumption, technology-cost, and policy-target data are compiled to establish the baseline year and boundary conditions. Second, the LEAP (Long-range Energy Alternatives Planning) model is used to project sectoral hydrogen demand under multiple policy-constrained scenarios, including industrial feedstock substitution, transportation fuel-cell deployment, power-sector storage, and building applications. Third, a system dynamics module simulates supply-chain evolution, including the changing shares of fossil-based hydrogen, industrial by-product hydrogen, and renewable hydrogen, as well as feedback from electrolyzer learning curves, renewable electricity prices, infrastructure expansion, and carbon pricing. Fourth, Levelized cost of hydrogen (LCOH) calculations and life-cycle assessment are applied to compare production pathways and to test whether the resulting cost and emission trajectories are consistent with the three-stage roadmap.

Key assumptions include: (1) learning-curve effects for electrolyzer costs declining at 8%–12% annually; (2) renewable electricity price trajectories based on National Energy Administration projections and cited sectoral studies; (3) a carbon price trajectory increasing from 150 yuan/ton in 2030 to 300 yuan/ton in 2060; and (4) technology maturity thresholds aligned with China Hydrogen Alliance roadmaps and the cited literature. The model outputs are not intended to provide a single-point forecast. Instead, they indicate the range and timing under which hydrogen could shift from project-level demonstration to system-level deployment. Sensitivity checks are conducted around electrolyzer cost, renewable electricity price, carbon price, and infrastructure utilization rate to identify the main factors affecting the 2030, 2040, and 2060 transition milestones.

The 8%–12% annual electrolyzer cost-reduction range is used as a learning-rate parameter rather than as a fixed engineering prediction. It reflects the rapid cost decline observed in China's alkaline and PEM electrolyzer manufacturing, while also allowing for uncertainty in catalyst use, stack lifetime, system integration, and production scale-up[17]. The assumed carbon price trajectory is a policy-scenario parameter. The 150 yuan/ton value for 2030 represents a moderate strengthening of China's carbon market relative to its current early-stage level, whereas the 300 yuan/ton value for 2060 represents a gradually tightened carbon constraint under the carbon-neutrality target. These assumptions are therefore used to test the conditions under which low-carbon hydrogen becomes competitive; they are not treated as deterministic policy forecasts.

Figures 1–3 summarize the key model trends that support the staged roadmap. Figure 1 indicates that fossil-based hydrogen remains dominant before 2030, while renewable hydrogen expands rapidly after 2035 and becomes the main source under the 2060 scenario. Figure 2 shows that industrial demand remains the largest consumption segment, but transportation, power-sector storage, and building applications gradually increase their shares as infrastructure improves. Figure 3 highlights that green-hydrogen costs decline within a range rather than along a single deterministic path. The lower-bound trajectory reflects faster learning and cheaper renewable electricity, whereas the upper-bound trajectory reflects slower technology progress and higher system-integration costs.

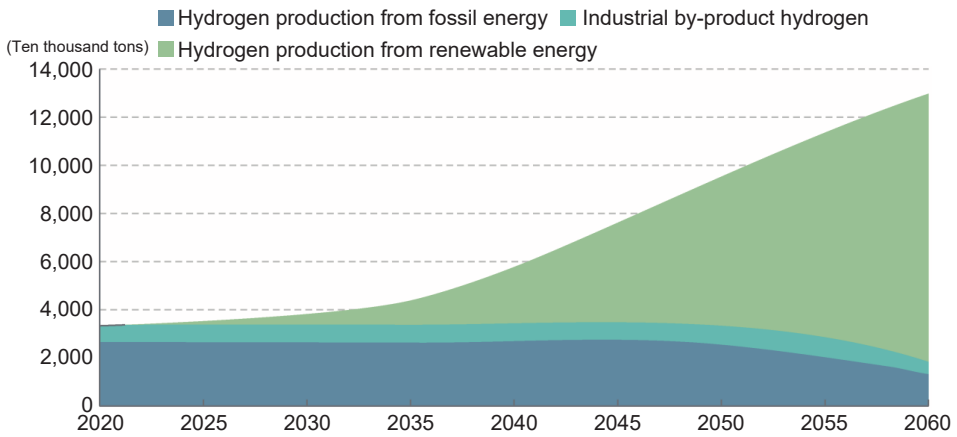


Fig. 1. Scale development and forecast of China's hydrogen supply system.

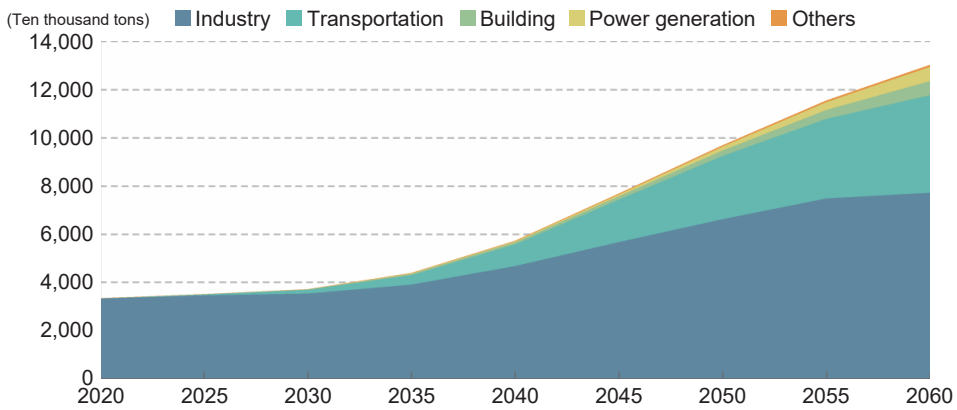


Fig. 2. Scale development and forecast of China's hydrogen consumption system.

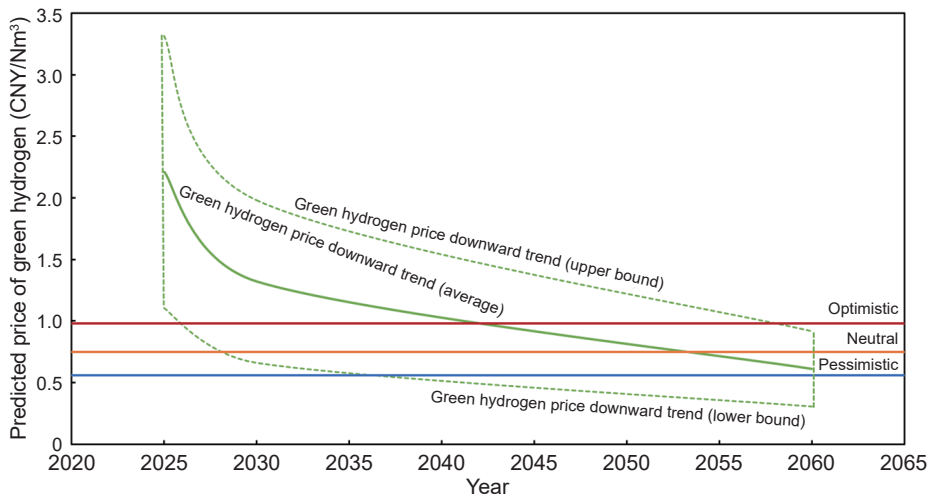


Fig. 3. China's green hydrogen price forecast.

3. A three-stage roadmap

These three stages are derived from a systematic analysis of national and provincial hydrogen-energy policies, model-based cost and supply-demand inflection points, and implementation timelines. The stage boundaries therefore reflect both policy milestones and modeled changes in economic competitiveness, infrastructure coverage, and system-integration capability. In this paper, scenario enablement refers to the use of hydrogen in specific industrial, transport, or demonstration applications where it helps solve local decarbonization problems but does not yet reshape the wider energy system. System regulation refers to hydrogen's ability to provide long-duration storage, cross-regional energy transfer, peak shaving, and cross-sector coordination when renewable power penetration rises. The foundational energy-carrier role refers to a mature stage in which hydrogen complements electricity as a storable, transportable, and molecule-based energy carrier for sectors that are difficult to electrify directly. It is proposed that China's hydrogen industry may follow this sequence from now to 2060 (Fig. 4), supported by continuous progress in technology, standards, market mechanisms, and safety regulation.

3.1 Current phase (through 2030): scenario enablement and technology validation

Results indicate that during the current phase, China's energy system remains dominated by

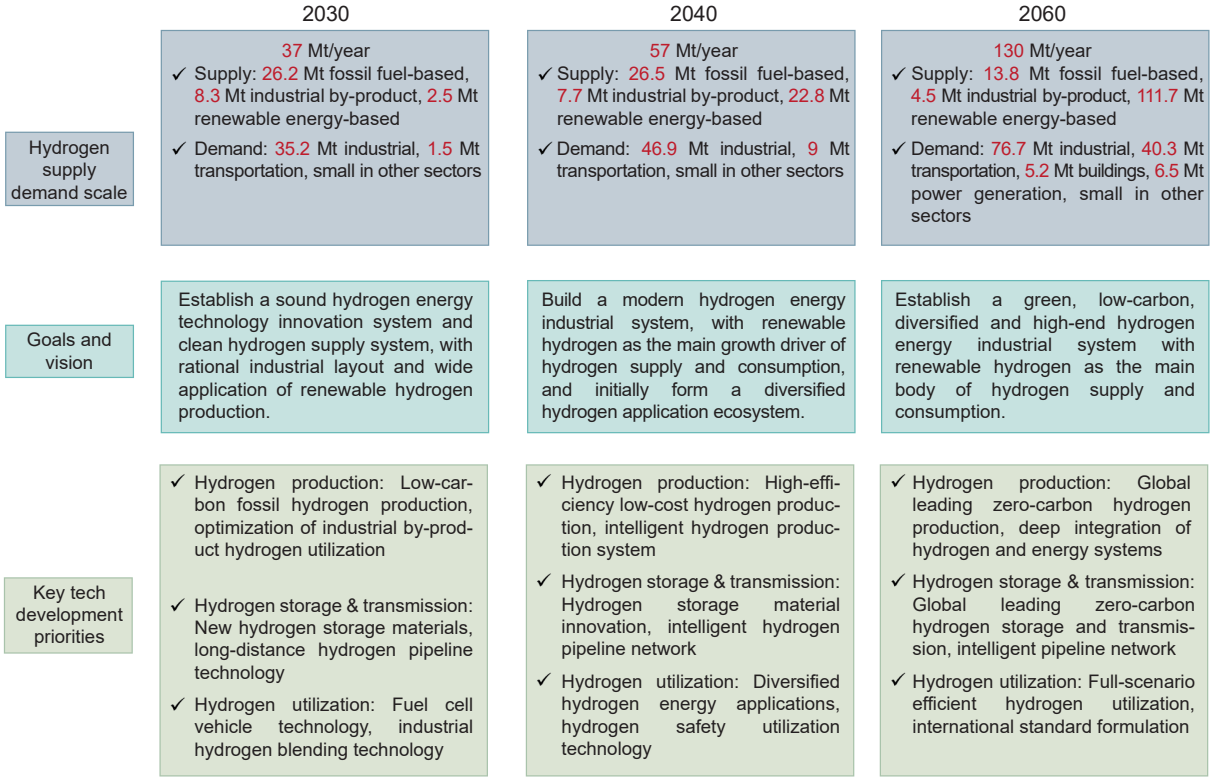


Fig. 4. A three-stage roadmap for China's hydrogen energy industry development: market size, role, and key technology development priorities

fossil fuels, with non-fossil energy sources playing a supplementary role. In 2024, non-fossil energy accounted for less than 20% of China's primary energy consumption[7]. Hydrogen energy has yet to be integrated into the core architecture of the energy system, its function limited to enabling specific scenarios. This manifests primarily in replacing a small portion of high-carbon raw materials in industrial applications[18-20].

Representative demonstration projects validate the technical feasibility assumed in the model, but they also show that hydrogen deployment remains project-based rather than commercially replicated. For example, integrated wind-solar-storage hydrogen projects coupled with coal chemicals and transport applications demonstrate the feasibility of connecting production, storage, transportation, and utilization, yet their scale, economics, and safety management still depend heavily on local policy support and project-specific coordination

The main bottlenecks are therefore more important than the individual demonstrations themselves. First, safety oversight and technical compatibility remain insufficient for large-scale cross-regional deployment. Second, storage and transportation still rely excessively on high-pressure gaseous routes, which concentrates safety risk and limits transport distance. Third, fragmented standards across production, storage, transportation, refueling, and end-use equipment hinder coordination among regions and sectors. Fourth, renewable hydrogen still has weak market competitiveness because production costs remain high and business models depend on subsidies or local demonstration policies[21-24].

3.1.1 Hydrogen production structure

Regarding hydrogen production structure, statistical modeling reveals a pattern dominated by fossil fuels, with renewable hydrogen production in its early stages of development. In 2024, China's hydrogen output exceeded 36.5 million tons, with coal-based hydrogen accounting for 56%, natural gas-based hydrogen for 21%, industrial by-product hydrogen for 21%, and renewable hydrogen production contributing less than 2%[25].

Techno-economic calculations demonstrate that fossil fuel-based hydrogen production technologies have achieved full commercial maturity. Coal-based hydrogen production costs as low as 6–12 yuan/kg and can reliably support the rigid hydrogen demand in industrial sectors such as synthetic ammonia and methanol production. Coke oven gas and by-product hydrogen from chlor-alkali production, purified via pressure swing adsorption (PSA) technology, can achieve 99.999% purity at a cost of 6–16 yuan/kg, making it the primary hydrogen source for early-stage transportation applications.

Technology readiness assessments reveal alkaline water electrolysis technology has completed commercial demonstration, while proton exchange membrane (PEM) electrolysis is undergoing system-level demonstration. However, constrained by electrolyzer equipment costs and renewable electricity price volatility, renewable hydrogen production costs range from 15 to 51 yuan/kg, gradually gaining market competitiveness[26].

3.1.2 Storage and transportation constraints

The system primarily relies on high-pressure gaseous technology, with other technical routes still in the exploratory phase. High-pressure gaseous hydrogen storage technology exhibits the highest maturity, with 35 MPa Type III vehicle-mounted storage cylinders achieving large-scale application. Long-tube trailers transport approximately 400 kg of hydrogen per vehicle, accounting for 98% of the nation's total hydrogen storage and transportation volume. This technology is suitable for short-distance transportation scenarios within 200 kilometers[26].

Cryogenic liquid hydrogen storage remains in the pilot testing phase, with limited application only in specialized scenarios such as aerospace and high-end transportation[27]. Similarly, solid-state hydrogen storage technology remains in the laboratory validation stage. Although some solid-state storage projects have achieved a capacity of 48,000 standard cubic meters, large-scale application faces constraints due to issues like high material costs and a cycle life of less than 1,000 cycles[28].

Regarding hydrogen transportation methods, road transport remains the absolute mainstream. Pipeline hydrogen transportation currently covers less than 500 kilometers. Cross-regional pipelines like the "West Hydrogen to East" project are still in the planning and construction phase, failing to establish networked hydrogen transportation

capabilities. As our gap analysis shows, the lack of standards for pipeline material compatibility with hydrogen and leak detection technologies constrains the development of cross-regional hydrogen transportation[29-31].

3.1.3 End-use applications

End-use application modeling demonstrates that hydrogen application focuses on foundational support in the industrial sector and breakthrough exploration in transportation. The industrial sector currently represents the primary application scenario for hydrogen energy[32], with hydrogen used in synthetic ammonia and methanol production accounting for over 50% of national hydrogen consumption in 2024. Hydrogen metallurgy demonstration projects can significantly reduce carbon emissions per ton of steel, yet our capacity tracking shows such initiatives cover less than 1% of the nation's steel production capacity[33].

The five designated fuel cell vehicle demonstration city clusters—Beijing–Tianjin–Hebei, Shanghai, Guangdong, Zhengzhou, and Hebei—have cumulatively deployed over 15,000 fuel cell vehicles, falling short of the projected 35,000-vehicle target by the end of 2025. Hydrogen applications in power generation and buildings have reached technical readiness levels, while projects like hydrogen energy storage and hydrogen blending with natural gas have yet to achieve scaled application effects.

3.1.4 System integration limitations

At the current stage, hydrogen mainly plays a scenario-enabling role because cost and compatibility constraints prevent wider system integration. Renewable hydrogen remains 3–5 times more expensive than fossil-based hydrogen production, storage and transportation networks do not yet cover major demand areas, and end-use equipment retrofitting remains costly. In parallel, safety regulation, carbon accounting, and cross-regional standards are still incomplete. These factors confine hydrogen to policy-driven industrial and mobility applications and prevent it from functioning as a system-wide balancing resource before 2030.

3.2 Mid-term phase (2030–2040): system regulation and cross-sector integration

3.2.1 Long-term energy system projections

The strategic milestone of establishing a new power system by 2040 is expected to elevate hydrogen's role from scenario enablement to system regulation within the energy system. By this stage, China's renewable energy share is projected to exceed 40%[34]. The fluctuating and intermittent nature of wind and solar power generation may pose increasing challenges to grid stability. Under favorable cost and infrastructure conditions, hydrogen could assume critical functions in long-duration energy storage, cross-regional energy transmission, flexible peak shaving, and industrial feedstock substitution. It may also serve as an energy hub connecting the power, industrial, and transportation sectors, thereby supporting renewable-power integration, energy security, and low-carbon transition.

Techno-economic projections demonstrate that this transition depends on the convergence of three key conditions. First, renewable hydrogen must approach a market-acceptable cost range through lower electrolyzer costs, cheaper renewable electricity, and higher equipment utilization. Second, pipeline, storage, and refueling networks must expand sufficiently to connect renewable-resource bases with industrial and transportation demand centers. Third, safety regulation, low-carbon certification, grid-dispatch rules, and cross-sector standards must become consistent enough to support routine commercial operation rather than isolated demonstration projects. If these conditions are met, hydrogen can move from enabling individual scenarios to performing system-regulation tasks; if they are delayed, the 2040 role of hydrogen would remain more limited and regionally uneven.

3.2.2 Hydrogen production cost trajectory

The core breakthrough in hydrogen production is expected to be a gradual narrowing of the cost gap between renewable hydrogen and fossil fuel-based hydrogen, although challenges remain in technical stability, large-scale supply, and low-carbon certification. Under the modeled scenarios, renewable hydrogen production costs may fall to approximately 10–21 yuan/kg by 2030 and 9–18 yuan/kg by 2040.

Key technological advancements are likely to occur in electrolysis. First, alkaline water electrolysis cells have achieved conversion efficiencies exceeding 70%, with equipment costs falling below 700 yuan/kW. However, consistency and longevity under mass production still require improvement. Second, PEM electrolysis may reduce precious-metal catalyst use through optimization, lowering equipment costs to under 1500 yuan/kW in favorable scenarios. Nevertheless, catalyst resistance to poisoning and long-term stability require further validation. Third, rapid declines in renewable electricity generation costs could drive reductions in renewable-hydrogen levelized costs. However, renewable-power intermittency will continue to affect the stable operation of hydrogen production systems, requiring complementary storage or hybrid operation strategies.

Supply-structure projections suggest that renewable hydrogen could account for about 40% of total hydrogen supply by 2040, roughly approaching the scale of fossil-based hydrogen in the modeled scenario. Renewable hydrogen may gradually shift from policy-supported demonstration toward market-based competition. Establishing unified low-carbon certification standards and clear carbon-accounting methods will be essential to ensure its low-carbon credentials[35].

3.2.3 Storage and transportation network evolution

During this phase, hydrogen storage and transportation development is expected to focus on expanding domestic pipeline networks and advancing storage technologies to support cross-regional hydrogen supply and flexible delivery.

Pipeline network expansion. Pipeline transport is likely to become a key breakthrough direction for this phase. By 2040, the national hydrogen pipeline network could exceed 10,000 kilometers under an accelerated infrastructure scenario. Hydrogen pipelines, such as the "West Hydrogen to East" project, are expected to improve cross-regional allocation and reduce transportation costs, although the pace of expansion will depend on utilization rates, safety standards, and investment mechanisms.

High-pressure gaseous storage advancement. High-pressure gaseous hydrogen storage technology is expected to advance toward 70 MPa Type IV storage cylinders. Long-tube trailers may achieve higher hydrogen transport capacity per vehicle and remain suitable for short-distance flexible delivery. Safety-inspection standards and end-of-life disposal systems for high-pressure storage cylinders must be refined to mitigate usage risks.

Cryogenic and underground storage. Energy consumption for cryogenic liquid hydrogen storage is expected to decline, potentially approaching below 12 kWh/kg, with daily evaporation loss rates under 0.5% under advanced-technology assumptions. This route may be applied first in long-distance and high-value-added scenarios. However, thermal-insulation standards and transportation safety regulations still require refinement. Geological capacity assessments suggest that large-scale underground hydrogen storage could provide seasonal peak-shaving capacity, but its deployment will depend on site-specific safety assessment, seal-integrity testing, and environmental-risk prevention standards.

3.2.4 Multi-sector application scaling

Hydrogen energy applications are expected to expand through industrial decarbonization, transportation scaling, and selected breakthroughs in power-sector storage.

Industrial sector decarbonization. Hydrogen metallurgy capacity could exceed 10 million tons by 2040 in the modeled scenario, covering approximately 10% of China's steel production capacity. Renewable-hydrogen chemical production capacity may also surpass 5 million tons. Safety protocols for hydrogen metallurgy, equipment technical standards, and quality standards for renewable-hydrogen chemical products must be established.

Transportation sector scaling. Fuel cell heavy-duty trucks could be deployed at a scale exceeding 100,000 units under favorable infrastructure and cost conditions, particularly in ports, mining areas, and long-haul logistics. A hydrogen refueling infrastructure network may develop following a "trunk corridor and regional

network" layout. Unified technical standards for fuel cell heavy-duty trucks and refueling-station specifications are required to reduce industrial coordination costs.

Power sector application. Hydrogen energy storage and peak-shaving capacity could exceed 10 GW under the modeled pathway, helping accommodate output fluctuations from wind and solar bases. Grid-integration standards and dispatch protocols for hydrogen energy storage systems must be established to ensure stable and secure grid operation.

Building sector application. Hydrogen blending in natural gas may increase to 10%–20% in selected regions. Hydrogen-blended natural gas supply could cover over 1 million households in provinces and cities such as Shandong, Beijing, Guangzhou, and Sichuan without requiring large-scale retrofits to existing pipelines. Standards for hydrogen blending ratios, pipeline-material impacts, and residential gas safety measures must be clarified.

3.2.5 System regulation role

At this stage, hydrogen is expected to assume a system-regulation role if technological maturity, safety assurance, standardization, and energy-system demand become sufficiently aligned. Renewable hydrogen costs may reach a market-acceptable threshold, storage and transportation networks may cover major supply and demand regions, and the cost of end-use equipment retrofitting may decline. In this case, hydrogen could undertake systemic tasks such as renewable-energy integration, grid peak shaving, and industrial decarbonization, positioning it as a bridging agent within the energy system. However, regional imbalances, uneven implementation of standards, and risks associated with technological iteration will still require continuous monitoring.

3.3 Long-term phase (2060): foundational energy carrier and global leadership

3.3.1 2060 energy system architecture

By 2060, non-fossil energy sources are expected to account for over 80% of China's primary energy consumption under the carbon-neutrality pathway. Hydrogen could evolve from a system-regulation resource to a foundational energy carrier, providing support for energy security, renewable-electricity integration, and deep decarbonization. At the production end, hydrogen may convert surplus renewable electricity into storable chemical energy. At the consumption end, it could substitute fossil fuels and fossil feedstocks in selected industrial and transportation sectors. At the system end, it may improve coordination among multiple energy sources and become an important end-use energy form alongside electricity.

Technological development modeling in this phase exhibits core characteristics of full industrial chain autonomy and controllability, absolute dominance of renewable hydrogen, and deep penetration across multiple sectors. It also establishes a comprehensive safety assurance system covering the entire lifecycle and an internationally aligned standard system. However, challenges remain, including global hydrogen competition, continuous technological iteration, and ensuring energy security under extreme scenarios[36].

3.3.2 Hydrogen production: renewable dominance

The hydrogen production segment is expected to develop a supply system centered on renewable hydrogen, while strengthening technological self-reliance and participation in international standard setting.

Supply structure transformation. Renewable energy-based hydrogen production is expected to become the dominant force in hydrogen supply under the 2060 scenario. The share of fossil fuel-based hydrogen production may be significantly reduced and, where retained, would need to be supported by carbon capture, utilization, and storage (CCUS) technologies to achieve low-carbonization. Industrial by-product hydrogen is likely to serve mainly as a supplementary source.

Advanced production technologies. Solid oxide electrolyzer hydrogen production may achieve commercial deployment, with conversion efficiency and equipment economics approaching internationally leading levels. Anion exchange membrane electrolyzer hydrogen production could also achieve scaled application. Further breakthroughs may occur in nuclear hydrogen production and direct seawater hydrogen production, although their commercial timing remains uncertain.

Supply chain development. Coastal regions may develop international liquid-hydrogen trade hubs and integrate hydrogen into global energy commerce while promoting low-carbon certification and trade standards. Cost modeling suggests that renewable hydrogen could decline to market-competitive levels, enabling broader substitution for fossil-based hydrogen and reshaping hydrogen supply structures.

3.3.3 Integrated storage and transportation networks

Hydrogen storage and transportation are expected to evolve toward an integrated network covering major domestic demand regions and selected international connections.

Domestic pipeline backbone. Domestically, a hydrogen pipeline backbone may be established, with expanded pipeline mileage and lower transportation costs supporting large-scale cross-regional hydrogen allocation.

Advanced storage technologies. Energy efficiency in cryogenic liquid hydrogen storage technology may improve substantially to meet selected transoceanic hydrogen trade demands. Solid-state hydrogen storage materials could achieve practical standards for cycle life and cost if material breakthroughs continue. These materials may then be adopted in distributed hydrogen applications.

Global standards leadership. China may play a more active role in establishing global hydrogen storage and transportation standards. It could promote hydrogen-networks interconnection with neighboring regions and participate in international hydrogen supply chains, although this process will depend on trade rules, certification alignment, and geopolitical conditions.

3.3.4 Deep sectoral penetration

Hydrogen applications are projected to deepen across multiple sectors, with the extent of penetration depending on cost, infrastructure, and competing low-carbon technologies:

Industrial sector. Technologies such as hydrogen metallurgy and renewable-hydrogen chemical processes could account for a large share of applications, helping replace fossil-based raw materials and reduce carbon emissions in high-energy-consuming industries such as steel.

Transportation sector. Fuel cell technology may account for a substantial share of long-distance applications such as heavy trucks, ships, and aviation, where batteries face energy-density or refueling-time constraints. The passenger vehicle sector is more likely to develop an "electricity-hydrogen" synergistic supply model to accommodate diverse mobility needs.

Power sector. Hydrogen energy storage and peak-shaving capacity could expand significantly, supporting the stable operation of high-penetration non-fossil power systems.

Building sector. Hydrogen fuel cell combined heat and power systems may be applied in selected commercial buildings, enhancing overall energy-utilization efficiency. Hydrogen heating could become one option within a power-hydrogen coordinated heating system, although its market share will depend on cost, safety regulation, and competition from electrified alternatives.

3.3.5 Foundational energy-carrier role

At this stage, hydrogen serves as a foundational energy carrier rather than merely a supplementary fuel. This conclusion is driven by the structural limits of direct electrification in several parts of the energy system. Electricity is highly efficient for many end-use applications, but it is less suitable for large-scale seasonal storage, some high-temperature industrial processes, molecule-based feedstocks, and long-distance heavy transport. Hydrogen can fill these gaps by converting surplus renewable electricity into a storable and transportable chemical energy carrier, by replacing fossil feedstocks in steel and chemicals, and by providing high-energy-density fuels for heavy-duty transport, shipping, and aviation. Under

this division of functions, electricity becomes the dominant carrier for direct electrification, while hydrogen provides molecule-based storage, feedstock substitution, and system resilience. The result is a dual-carrier energy architecture in which hydrogen and electricity reinforce each other rather than compete.

This foundational role also depends on the maturity of the full industrial chain. By 2060, renewable hydrogen could become one of the economically viable clean energy sources if advanced electrolysis, integrated storage and transportation networks, low-carbon certification, and full-lifecycle safety governance continue to mature. Hydrogen may therefore become embedded in production and daily life, not only as an energy carrier but also as a strategic tool for green industrial transformation, emergency energy security, and international energy cooperation[37].

4. Discussion

The three-stage roadmap outlines a technically feasible pathway, but its realization is not automatic. Several structural uncertainties extend beyond the techno-economic parameters modeled above. These uncertainties do not invalidate the roadmap; rather, they define the boundary conditions for policy design, infrastructure investment, and future research.

Technology maturation and resource constraints. Our cost projections assume sustained electrolyzer learning, but energy transitions often show path-dependent inertia. For example, solid-state hydrogen storage has remained in laboratory demonstration for decades. If cycle life and cost do not improve substantially by 2035, high-pressure gaseous storage may remain dominant for longer than expected, favoring industrial feedstock use over mass-market energy storage. Pipeline development also faces material-compatibility risks. If hydrogen embrittlement is more severe than assumed, new pipeline construction could increase infrastructure costs. In addition, fugitive hydrogen emissions above 2%–3% of production would weaken climate benefits, given hydrogen's indirect warming effect. Large-scale electrolysis would also require substantial purified water, which may constrain production in water-scarce northern regions where renewable resources are abundant.

Competition from adjacent technologies. The roadmap assumes hydrogen retains comparative advantage in specific niches, yet technological disruption could narrow these windows. Solid-state batteries approaching 400 Wh/kg by 2030–2032 might reduce the cost advantage of fuel cells in heavy-duty trucking before refueling networks achieve critical mass. Likewise, compressed air and liquid air storage currently show faster cost decline rates than hydrogen storage; if they reach $100/(kWh) by 2038–2040, hydrogen's grid role may concentrate in seasonal arbitrage rather than daily cycling. Continuous technology monitoring is therefore essential to avoid stranded assets, particularly during the 2030–2040 decision window when infrastructure investments lock in.

Supply chain resilience and standard alignment. China's current dominance in electrolyzer manufacturing—accounting for over half of global capacity at $480–720/kW compared to $2,000–3,000/kW in Western markets—provides a substantial buffer against supply disruptions that could delay cost parity elsewhere by 5–7 years. However, reliance on platinum group metals and carbon fiber from politically unstable regions remains a vulnerability. Moreover, divergent certification standards (EU-centric "renewable-only" versus broader low-carbon definitions) may segment global markets. China's ability to maintain supply chain access while shaping internationally aligned standards will determine whether it captures premium market segments or faces isolation from premium hydrogen trade flows.

Institutional adaptation. The Energy Law provides foundational reclassification of hydrogen as an energy source, yet secondary regulations including building codes, safety standards, and grid protocols require decade-long revision cycles. Historical experience from natural gas market reform suggests that infrastructure unbundling faces 10–15 year lags due to incumbent resistance; hydrogen pipelines may remain vertically integrated rather than the open-access common carriers assumed in our model, potentially distorting regional price signals and allocation efficiency.

These uncertainties require adaptive transition strategies. The 2030 milestone should be treated as a reassessment point rather than a fixed commitment. If electrolyzer costs decline below about 600 yuan/kW and storage costs fall below about 15 yuan/kg-H_2, hydrogen's system-regulation role can expand with greater confidence. If these thresholds are not reached, public support and private investment should shift toward alternative storage, electrification, or hybrid pathways to avoid stranded assets. This implies a move from static roadmaps toward dynamic transition management based on continuous monitoring of technology costs, competing storage solutions, infrastructure utilization, and regulatory progress.

The policy implications are threefold. First, near-term support should be technology-neutral and evidence-based. Demonstration projects should generate verifiable data on cost, safety, leakage, water use, and carbon intensity rather than pursue deployment scale alone. Second, mid-term infrastructure investment should be linked to staged utilization and safety thresholds, especially for pipelines, underground storage, and refueling corridors. Network expansion should follow demand formation. Third, future research should strengthen spatially resolved modeling of renewable resources, water constraints, hydrogen leakage, pipeline material compatibility, and competing storage technologies. Integrating these topics into the LEAP-system dynamics framework would improve future roadmap updates and help policymakers adjust the pace of deployment as evidence accumulates.

5. Conclusion

With accelerating energy-structure transformation, China's hydrogen industry is expected to advance through three broad stages: scenario enablement, system regulation, and foundational energy-carrier development. The pathway depends on technological progress, cost reduction, safety assurance, standard-setting, and market mechanisms. In hydrogen production, the key task is to reduce renewable-hydrogen costs while improving the stability of renewable-power-based production. In storage and transportation, the priority is to build multi-modal networks supported by safety technologies and unified standards. In end-use applications, sector-specific standards and operating protocols are needed to support wider adoption in industry, transport, power, and buildings. If these conditions are met, hydrogen and electricity could form a dual-carrier energy structure that supports China's deep decarbonization. At the same time, the limitations discussed above should remain central to policy design. Technological uncertainty, competing low-carbon technologies, resource and water constraints, hydrogen leakage, geopolitical competition, and infrastructure lock-in risks may all affect the scale and timing of deployment. Continuous monitoring, adaptive policy design, and international cooperation are therefore necessary to ensure that hydrogen develops from a supporting fuel in selected applications into a reliable molecule-based carrier within a clean, low-carbon, and efficient energy system.

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Author contribution statement

Quan Cao: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization. Qing Lin: Investigation, Validation, Writing – review & editing. Hongjian Wang: Investigation, Data curation, Formal analysis. Congmin Liu: Resources, Investigation. Shuang Li: Methodology, Validation. Siqi Wang: Investigation, Visualization. Chang Liu: Data curation, Validation. Ziwei Du: Investigation, Formal analysis. Yuqing Wang: Resources, Writing – review & editing. Yanfei Zhao: Supervision, Resources, Writing – review & editing. Yixiang Shi: Conceptualization, Supervision, Project administration, Writing – review & editing.

Data availability

Not applicable.

Use of AI statement

During the preparation of this work, the authors used ChatGPT in order to improve language and readability. After using this tool, the authors reviewed and edited the content and take full responsibility for the content of the publication.

Declaration of competing interest

Quan Cao, Hongjian Wang, Siqi Wang, and Ziwei Du are employees of Beijing Gas and Heating Engineering Design Institute Co., Ltd. Congmin Liu, Chang Liu, and Yanfei Zhao are employees of CHN ENERGY Hydrogen InnovationTechnology Co., Ltd. The authors have no competing interests to declare that are relevant to the content of this article.

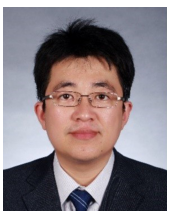
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