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Development of hydrogen energy and estimation of policy subsidy intensity: a benchmarking analysis based on wind and solar energy development

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As the main driving forces of renewable energy, wind and photovoltaic power have important reference value for the emerging hydrogen energy industry in aspects such as policy guidance, technological innovation, and market cultivation. As a zero-carbon energy carrier, hydrogen energy can not only alleviate the intermittency of wind and solar power generation and enhance grid stability, but can also contribute to deep decarbonization across multiple sectors. At present, China's hydrogen energy industry faces many challenges, including a low degree of localization, high costs, and incomplete standards. This article reviews key policies supporting the development of the wind and solar energy industries and, through benchmarking analysis, systematically evaluates the directions that the hydrogen energy industry can learn from. Furthermore, drawing on the experience of the wind and solar industries in promoting localization driven by policy subsidies during their early stages, a model for estimating the intensity of hydrogen energy policy subsidies is constructed to analyze subsidy requirements under different learning rates. It is found that a benchmark learning rate of 18% achieves an optimal balance. Based on the evaluation and analysis, several targeted suggestions are proposed to help the hydrogen energy industry overcome bottlenecks and achieve high-quality, large-scale development: strengthening innovation and intellectual property layout in key technologies such as electrolyzers and hydrogen storage materials; improving industry chain standards including the definition and certification of green hydrogen; deepening international cooperation with technologically leading countries; and promoting demonstration projects such as green hydrogen production and hydrogen-powered heavy-duty trucks.

KEYWORDS

hydrogen energy industry, wind and solar energy, green hydrogen, benchmarking analysis, subsidy intensity estimation model

1 Introduction

In recent years, the global fossil energy crisis has intensified, extreme weather events have occurred with increasing frequency, and the transformation of the energy structure toward cleaner and lower-carbon forms has become increasingly urgent. As two core pillars of the clean energy system, wind and photovoltaic power are being vigorously developed and promoted worldwide Figure 1 shows China's current energy structure. Although China entered the wind and photovoltaic industries relatively late, it has evolved from a technological follower to a global leader within just a few decades, becoming a main driving force in the energy system. Over the past decade, China's newly installed capacity of wind and photovoltaic power has shown an overall upward trend (Figures 2, 3). By the end of 2024, the cumulative installed capacity of wind power had reached 520.68 million kilowatts, while that of photovoltaic power had reached 886.66 million kilowatts (Liu et al., 2025). These remarkable achievements are inseparable from strong policy support and major breakthroughs in technological innovation. The phased development experience of the wind and photovoltaic industries offers valuable lessons for the full-cycle development of hydrogen energy.

Hydrogen, as an emerging energy source, possesses high energy density and excellent storability. Hydrogen production through water electrolysis can not only help alleviate the intermittency and uncertainty of wind and solar power generation and reduce the curtailment rate of new energy (Eladl et al., 2024), but can also enhance the power grid's supporting capacity (Schmidt et al., 2017), long-term stability, and flexibility in the context of a new power system (Yang et al., 2025). By the end of 2024, China's hydrogen production capacity had exceeded 50 million tons per year, with an annual hydrogen output exceeding 36.5 million tons. Hydrogen derived from fossil fuels continued to dominate the supply structure, accounting for approximately 77%, while hydrogen produced through water electrolysis represented only about 1% (Figure 4) (Energy Conservation and Science, 2025).

At present, China's hydrogen energy industry faces multiple challenges (He and Shen, 2021):

1. Core technologies for hydrogen production via water electrolysis have yet to achieve major breakthroughs, and key components remain dependent on imports;
2. The full life-cycle cost of hydrogen energy projects remains high, making it difficult for industries to survive;
3. The industrial structure and policy supervision mechanisms require further improvement.

These challenges hinder large-scale hydrogen production in the upstream segment, increase costs in midstream storage and transportation, and place heavy burdens on downstream applications. Consequently, market activation is limited, forming a bottleneck in the overall development of China's hydrogen energy industry.

The current stage of hydrogen energy development shows similarities to the early take-off period of the wind and solar energy industries. This article systematically reviews the development

TABLE 1 Policy experiences that the hydrogen energy industry can learn from.

Development stage	Core experience	Benchmarking direction for the hydrogen energy industry
Slow start-up period	Strategic planning: Introduction of the *Energy Policy Outline* to define the development direction, and inclusion of wind and solar energy in the *Sixth Five-Year Plan* Policy subsidies: The *Brightness Project* and *Wind Riding Plan* leveraged market mechanisms to promote localization, while wind power concession operations encouraged cost reduction	Formulate a special plan for hydrogen energy, clarify its positioning and technical pathways, and incorporate it into the national energy strategy Provide subsidies to support equipment localization, simulate the early market through government procurement, and explore franchising models for hydrogen energy development
Initial development period	Legislative guarantees: The *Renewable Energy Law* of 2005 established the principle of full purchase, which was refined through the 2009 revision Five pillars: Total target system, full absorption mechanism, classified electricity pricing, cost compensation, and special funds to support industrial development	Improve hydrogen energy legislation, clarify the principles and responsible entities for the full absorption of green hydrogen Set hydrogen energy development indicators, establish green hydrogen classification pricing and cost compensation mechanisms, and create special funds to support technological R&D
Structural adjustment period	Competitive pricing: The *Pioneer Program* promoted technological upgrading and cost reduction Subsidy reduction: A grid parity pilot was launched in 2019, achieving full grid parity by 2021	Launch the hydrogen energy *Pioneer Program* to promote technological iteration through competition mechanisms Establish a clear timetable for gradually phasing out green hydrogen subsidies, guiding enterprises to reduce costs through innovation
Parity maturity period	Consumption guarantee: Establishment of renewable energy consumption responsibility weights Scenario expansion: Implementation of the *Thousands of Towns and Villages Wind-Driving Action* and *Direct Green Power Connection*	Define a minimum consumption quota for green hydrogen to ensure market demand Promote rural hydrogen energy applications and direct green power connection projects to create characteristic demonstration zones for hydrogen energy utilization

TABLE 2 The case parameter assumptions.

Parameter name	Parameter value
Current cost C_0 (yuan/kg H_2)	35
Target cost C_{target} (yuan/kg H_2)	15
Market acceptable price P_{market} (yuan/kg H_2)	15
Current cumulative installed capacity Q_0 (GW)	4
Using hours (h/year)	3,000
Electrolyzer efficiency (kW/kg)	55
Project cycle (years)	10

TABLE 3 The estimation results of hydrogen energy subsidy-related parameters under a low learning rate.

Parameter name	Parameter value
Learning index *b*	0.1203
Cumulative installed capacity required to reach the target cost (GW)	1,145.44
Required new installed capacity (GW)	1,141.44
Cumulative hydrogen production (kg)	622.60×10^9
Total subsidy amount (100 million yuan)	62,260.42

TABLE 4 The estimation results of hydrogen energy subsidy-related parameters under the benchmark learning rate.

Parameter name	Parameter value
Learning index *b*	0.2863
Cumulative installed capacity required to reach the target cost (GW)	19.29
Required new installed capacity (GW)	15.29
Cumulative hydrogen production (kg)	8.34×10^9
Total subsidy amount (100 million yuan)	833.84

process and key policy experiences of China's wind and solar sectors and applies benchmarking analysis to identify policy directions that the hydrogen energy industry can draw upon at different development stages. On this basis, a model is constructed to estimate the intensity of hydrogen energy policy subsidies. Using learning curve theory, different learning rate scenarios are set to calculate the cumulative installed capacity and the corresponding subsidy scale required to achieve the target cost of green hydrogen. Finally, through a comprehensive evaluation of the model results, this study provides a quantitative foundation and pathway recommendations for overcoming the initial bottlenecks of the hydrogen energy industry and formulating effective support policies.

TABLE 5 The estimation results of hydrogen energy subsidy-related parameters under a high learning rate.

Parameter name	Parameter value
Learning index *b*	0.4739
Cumulative installed capacity required to reach the target cost (GW)	5.98
Required new installed capacity (GW)	1.98
Cumulative hydrogen production (kg)	1.08×10^9
Total subsidy amount (100 million yuan)	107.80

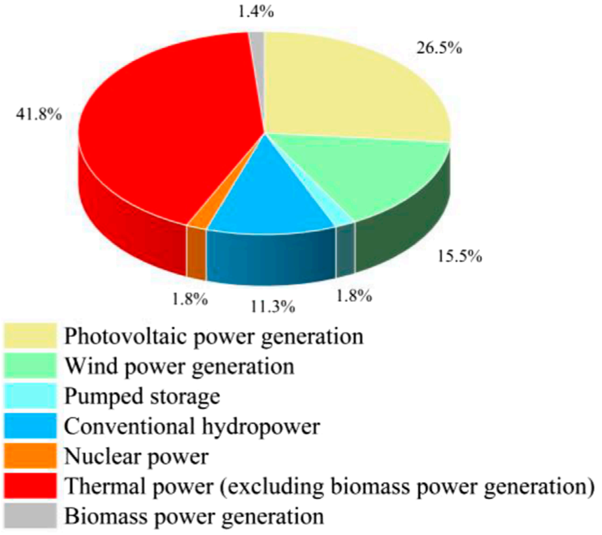

FIGURE 1
The proportion of installed capacity of various power sources in China in 2024.

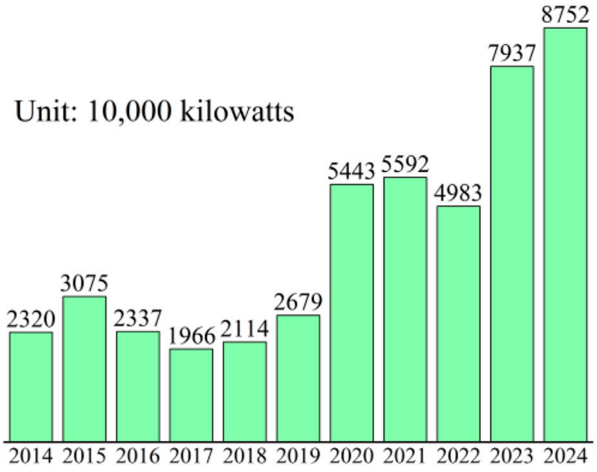

FIGURE 2
He newly installed wind power capacity in China from 2014 to 2024.

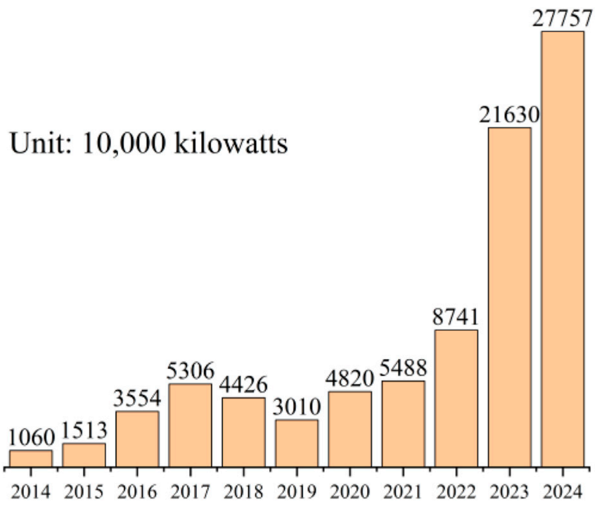

FIGURE 3
The newly installed photovoltaic capacity in China from 2014 to 2024.

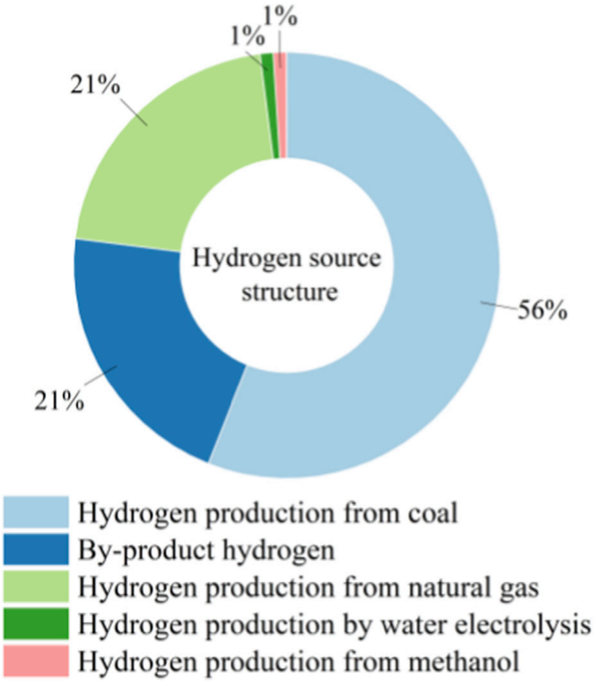

FIGURE 4
China's hydrogen source structure.

2 Key policy experiences in the development of the wind and solar energy industries

The rapid rise and transformation of China's wind and solar energy industries have attracted worldwide attention. From an early stage marked by dependence on foreign equipment, markets, and key raw materials, often described as "three external dependencies," to becoming the world's largest producer of wind and solar energy, this transformation has been driven by the coordinated advancement of policy, technology, and market forces (Yi et al., 2019). Reviewing the entire development trajectory of the wind and solar energy industries, their evolution can be broadly divided into four stages: the slow start-up period, the initial development period, the adjustment and fluctuation period, and the grid parity and expansion period.

The current vigorous growth of wind and solar energy is closely linked to scientific guidance and the strong promotion of national policies. Only by making correct choices at key nodes can leapfrog development be achieved, allowing the industries to avoid decades of exploratory detours.

The core experience of the slow start-up period can be summarized as "strategic planning anchors the direction, and policy subsidies drive localization." In terms of policy, the issuance of the first *Energy Policy Outline* proposed a sixteen-character guideline for new energy: "act in accordance with local conditions, complement multiple energy sources, utilize comprehensively, and emphasize benefits." This policy provided a fundamental framework for the scientific and orderly development of China's wind and solar energy industries. Even when viewed against the current state of renewable energy development, its guiding principles remain applicable, reflecting its foresight and enduring value. During the *Sixth Five-Year Plan*, renewable energy was incorporated into the scope of the national energy policy, and wind and solar energy were designated as key development areas. In 1997, the *Brightness Project* was launched, and the government's large-scale bidding and procurement of photovoltaic modules activated China's early photovoltaic market and promoted coordinated industrial chain development. In the same year, the *Wind Power Plan* was implemented, promoting equipment localization through central financial subsidies and laying the foundation for the subsequent industrial boom. In 2003, the introduction of the wind power concession policy marked a shift from a planned to a market-oriented development model, effectively forcing developers to reduce construction and operation costs.

The core experience of the initial development period can be summarized as "legislation to guarantee industrial status, and five pillars to safeguard industrial development." First, the total target system provided a clear top-level framework for industrial development. The *11th Five-Year Plan for Renewable Energy Development* was the first to specify quantitative development targets, while the *12th Five-Year Plan* further expanded these goals, effectively guiding social investment and setting the direction for industrial growth. Second, the full-guarantee purchase system was established to ensure the absorption of renewable energy power. Although the *Renewable Energy Law of 2005* (Chai et al., 2023) first introduced the principle of full purchase, its implementation faced difficulties due to the absence of detailed supporting measures. Following the 2009 revision, the system was concretized and institutionalized, which significantly improved its operability and provided a legal guarantee for the stable revenue of wind and solar power stations. Third, the classified electricity pricing system guided the rational layout of the industry through differentiated pricing (Qiu and Anadon, 2012). In 2009, the National Development and Reform Commission issued a policy dividing the country into four categories of wind energy resource zones and setting corresponding benchmark electricity prices. In 2013, it further defined photovoltaic benchmark prices for three types of solar energy resource areas

(Yu-Ling Hsiao et al., 2021). This approach effectively mitigated cost disparities arising from differences in resource endowments and encouraged enterprises to pursue orderly and balanced development nationwide. Finally, the cost compensation system and special fund system jointly addressed the issue of economic incentives for industrial development. The cost compensation system relied on a renewable energy surcharge, collected from electricity sales, to subsidize the portion of wind and solar power generation costs exceeding the local coal-fired benchmark electricity price (Zhao et al., 2014). Furthermore, the special fund system (such as the *Interim Measures for the Administration of Special Funds for Wind Power Equipment Industrialization* issued in 2008) adopted an "award instead of subsidy" approach to support technological research and development (R&D) and industrialization among equipment manufacturers. This promoted both localization and cost reduction in core technologies. Together, these two systems, acting from the power generation and manufacturing ends, respectively, formed the core driving force behind the initial phase of industrial development.

The core experience of the structural adjustment period can be summarized as "promoting quality improvement and cost reduction through competitive pricing, and achieving grid parity through the gradual phase-out of subsidies." In 2015, the National Energy Administration launched the *Pioneer Program* for photovoltaic power generation, which promoted technological upgrading and cost reduction in the photovoltaic industry by setting stringent technical indicators and introducing a market-oriented competition mechanism (Yu-Ling Hsiao et al., 2021). In 2016, the *Pioneer Program* for offshore wind power was introduced, aiming to advance technological progress and lower costs through the construction of a series of demonstration offshore wind power projects. In 2019, the National Development and Reform Commission issued the *Notice on Actively Promoting Work Related to Grid Parity for Wind Power and Photovoltaic Power Generation without Subsidies*, which explicitly called for the development of grid parity pilot projects and set the goal of achieving grid parity by 2021 (Tu et al., 2020).

The core experience of the parity maturity period can be summarized as "consolidating market space through consumption guarantees and addressing new challenges to promote high-quality development" (Wang et al., 2025). In 2019, the National Development and Reform Commission and the National Energy Administration jointly issued the *Notice on Establishing and Improving the Renewable Energy Power Consumption Guarantee Mechanism*, which set minimum renewable energy consumption responsibility weights to promote the development of wind and solar energy. In June 2022, the *14th Five-Year Plan for Renewable Energy Development* was issued, launching the *Thousands of Towns and Tens of Thousands of Villages Wind Control Action* to vigorously promote rural wind power development. At the same time, it introduced the *Thousands of Households Sunshine Action* to expand the comprehensive utilization of renewable energy in rural areas, promote the deployment of wind and solar projects in rural regions, and contribute to rural revitalization. On 30 May 2025, the National Development and Reform Commission and the National Energy Administration jointly issued the *Notice on Matters Concerning the Orderly Promotion of the Development of Direct Green Power Connection*, which, for the first time, established a national-level regulatory framework for the direct green power supply and consumption model. This policy aims to promote the local consumption of new energy and meet the green energy demands of enterprises, and holds significant importance for maintaining stable economic growth and achieving high-quality development.

The success of China's wind and solar energy industries is by no means accidental; it represents the comprehensive result of policy wisdom, technological resilience, and industrial perseverance. Their core experience can be summarized as follows: leveraging policy instruments to drive technological innovation, using market scale to dilute R&D costs, building a competitive moat through a complete industrial chain, and integrating into the global ecosystem with an open attitude. This development model, characterized by "government guidance, enterprise leadership, market operation, and global collaboration," offers valuable insights and references for the initiation and development of China's hydrogen energy industry. Table 1 shows the policy experiences from the wind and solar energy industries that the hydrogen energy industry can learn from.

3 Hydrogen energy policy subsidy intensity estimation model

According to the data released in the *Statistical Communiqué on National Economic and Social Development of the People's Republic of China* for 2024 (National Bureau of Statistics, 2025), China's total energy consumption in 2024 was 5.96 billion tons of standard coal. Combined with an annual hydrogen production of 36.5 million tons (Energy Conservation and Science, 2025) (equivalent to approximately 151 million tons of standard coal), the penetration rate of hydrogen energy can be estimated at about 3.0%. This penetration level indicates that the hydrogen energy industry remains in its embryonic stage. Drawing on the key policy experiences of the wind and solar energy industries analyzed through benchmarking in the previous chapter, it can be concluded that at the current stage, subsidy policies are essential to promote the localization of electrolyzers, thereby achieving the objectives of cost reduction and efficiency improvement.

3.1 Model establishment

The standard mathematical expression of the learning curve is as follows (Kahouli-Brahmi, 2008):

$$C_t = C_0 \times (Q_t)^{-b}, \tag{1}$$

in Equation 1 C_t represents the unit cost in year t; C_0 represents the unit cost in the initial year; Q_t represents the cumulative output or cumulative installed capacity (GW) by year t; and b represents the learning index.

The learning curve for hydrogen energy can be expressed as

$$\begin{aligned} C_{target} &= C_0 \times \left(Q_{target}\right)^{-b} \\ \Rightarrow Q_{target} &= \left(\frac{C_0}{C_{target}}\right)^{1/b}, \end{aligned} \tag{2}$$

in Equation 2 C_{target} is the target green hydrogen cost; C_0 is the current unit cost of hydrogen production by water electrolysis; and

Q_{target} is the cumulative installed capacity required to achieve the target cost. Moreover, the learning index $b = -\frac{\log(1-LR_H)}{\log(2)}$ is the learning rate of the hydrogen energy industry.

$$\Delta Q = Q_{target} - Q_0, \tag{3}$$

in Equation 3 ΔQ represents the newly added installed capacity, and Q_0 represents the current installed capacity of hydrogen energy.

The total required subsidy intensity can be calculated as

$$Subsidy\_total = \int_{Q_0}^{Q_{target}} (C(q) - P_{market})dq, \tag{4}$$

in Equation 4 $C(q)$ is the cost when the cumulative installed capacity is q, and P_{market} is the price acceptable to the market.

Because this integral calculation is relatively complex, this study simplifies the process by using the average cost gap, calculated as the average of the initial and target cost gaps.

Initial cost gap:

$$C_0 - P_{market} \tag{5}$$

Equation 5 is used to calculate the initial cost gap. Target cost gap:

$$C_{target} - P_{market} \tag{6}$$

Equation 6 is used to calculate the target cost gap. Given that the ultimate goal is to achieve green hydrogen grid parity, the target cost gap is set to 0, i.e., $C_{target} = P_{market}$.

Average subsidy intensity:

$$S\_avg = \frac{C_0 - P_{market} + C_{target} - P_{market}}{2} \tag{7}$$

Equation 7 is used to calculate the average subsidy intensity. Total subsidy:

$$Subsidy\_total \approx S_{avg} \times \Delta M, \tag{8}$$

in Equation 8 ΔM is the cumulative hydrogen output, which can be estimated as ΔQ (newly installed capacity in GW) × utilization hours × hydrogen production per unit capacity (kg/H_2/kW) × project cycle.

3.2 Calculation of subsidy intensity

Considering the variations in investment costs among different countries, it is hereby stated that all hypothetical results presented in this section were derived based on the current actual condition of China's hydrogen energy market. Table 2 shows the assumptions of relevant parameters.

Scholars such as Wang (Wang et al., 2022) fitted the global cumulative installed capacity and cost data of electrolyzers (most of which are alkaline electrolyzers, ALK) and obtained a learning rate of 18% for the electrolyzer system. Based on this finding, a hydrogen energy system learning rate of 18% was assumed, and a ±10% sensitivity analysis was conducted to simulate the effects of different learning rates.

Case 1: Low learning rate (8%). The relevant parameters are shown in Table 3.

Case 2: Base learning rate (18%). The relevant parameters are shown in Table 4.

Case 3: High learning rate (28%). The relevant parameters are shown in Table 5.

4 Results and discussion

Based on the estimation results of hydrogen energy subsidy-related parameters under different learning rate scenarios presented in Section 3.2, it can be observed that the learning rate directly influences the resource input and time frame required to achieve the target cost of green hydrogen (15 yuan/kg). The relationships among these three factors (learning rate, resource input, and time cycle) show significant negative correlations.

1. Low learning rate (8%) scenario: Under this scenario, the cumulative installed capacity required to reach the target cost is 1,145.44 GW, with a total subsidy amount reaching 6.23 trillion yuan. The industrial scaling process is relatively slow, and the efficiency of core technological breakthroughs and cost reduction remains low. This situation not only results in long-term fiscal pressure from high subsidy expenditures but may also delay the substitution process of green hydrogen for traditional energy sources. The imbalance between input and output makes it difficult for the industry's development pace to align with the zero-carbon energy transition required to achieve the dual-carbon goals.
2. Benchmark learning rate (18%) scenario: In this scenario, the cumulative installed capacity required to reach the target cost decreases significantly to 19.29 GW, with a total subsidy amount of 83.384 billion yuan. The subsidy scale remains within the fiscal capacity of public finance, while the cumulative installed capacity aligns with the current annual new installation levels of China's wind and solar industries. Under these conditions, the hydrogen energy industry can achieve steady scaling within a 10-year project cycle. The pace of green hydrogen cost reduction and market demand growth can reinforce each other, representing the optimal balance point between policy feasibility and sustainable industrial development.
3. High learning rate (28%) scenario: In this scenario, only 5.98 GW of cumulative installed capacity is required, with a total subsidy of 10.78 billion yuan. This outcome depends on rapid breakthroughs in core technologies, such as significant cost reductions in PEM electrolyzers and major improvements in the efficiency of hydrogen storage materials. Although this scenario could achieve green hydrogen grid parity at the lowest overall cost, it involves high uncertainty regarding the pace and feasibility of technological breakthroughs. Therefore, it cannot serve as a reliable plan for industrial development and should instead be regarded as an idealized target for guiding future technological research.

Based on the analysis of these three scenarios, the following conclusions can be drawn regarding the necessity of establishing subsidy policies for the hydrogen energy industry at the current stage.

4.1 Breaking the "high cost—low scale" vicious cycle in the early stage of the industry

The hydrogen energy industry remains in its infancy, in which the "high cost" of core equipment and technologies and the "low scale" of market applications constrain each other. The import dependency of key electrolyzer components is high, with a localization rate of less than 30%, and the cost of a single unit is five to eight times that of wind or solar power generation equipment. In 2024, hydrogen produced through water electrolysis accounted for only about 1% of China's total hydrogen supply, indicating that a large-scale market has yet to form, making it difficult for enterprises to amortize costs.

Subsidy policies can help break this closed loop. Drawing on the subsidy approaches of the *Wind Power Plan* and the *Brightness Project* in the wind and solar industries, providing R&D subsidies to electrolyzer manufacturers and production-based subsidies (per kilowatt-hour of hydrogen generated) to green hydrogen projects can reduce initial enterprise risks. Under the benchmark learning rate of 18%, a total subsidy of 83.384 billion yuan could drive the cumulative electrolyzer installed capacity from 4 GW to 19.29 GW, resulting in cumulative hydrogen production of 8.34×10^9 kg. This would form a positive development cycle of "subsidies driving scale–scale promoting cost reduction," helping to reduce the cost of green hydrogen from 35 yuan/kg to 15 yuan/kg.

4.2 Ensuring breakthroughs in the localization of the industrial chain

Significant gaps remain in China's hydrogen energy industry chain. In the upstream segment, over 80% of the core materials for electrolyzers still rely on imports. In the midstream segment, the performance of domestically produced materials for hydrogen storage containers remains insufficient. In the downstream segment, the degree of commercialization and market adoption of hydrogen applications is low. Without timely policy intervention, enterprises may abandon investment in core R&D, potentially repeating the early "three external dependencies" predicament of the photovoltaic industry.

At the current stage, subsidy policies should focus on promoting breakthroughs in localization. On the one hand, special subsidies should be provided for localization replacement projects, e.g., enterprises that successfully achieve localized production of PEM membranes and meet technical standards could receive rewards. On the other hand, drawing on the "subsidy linked to localization rate" mechanism in the wind and solar industries, it should be required that the localization rate of core equipment in green hydrogen projects reach no less than 70%, thereby encouraging collaborative innovation. The 2003 wind power concession policy used this approach, increasing the localization rate of equipment from less than 10% to more than 80% by 2010. This successful model can be adapted to the hydrogen energy field.

4.3 Connecting the dual-carbon goals with energy structure transformation

According to national plans, the proportion of non-fossil energy consumption in China should reach 25% by 2030, with the goal of achieving carbon neutrality by 2060. Hydrogen energy plays a crucial role in this transition, as it can absorb curtailed electricity from wind and solar power and This revision has not affected my intended meaning. However, the current penetration rate of the hydrogen energy industry is only 3.0%. If the industry relies solely on spontaneous market forces, the production of green hydrogen will fall short of meeting the industrial decarbonization demand by 2030, thereby hindering progress toward achieving the dual-carbon goals.

Subsidy policies thus serve as a key enabling mechanism. In the short term, a subsidy reduction mechanism linked to carbon prices can be established. Drawing on the gradual subsidy phase-out model from the wind and solar energy industries, such a mechanism could guide the market transition from "policy dependence" to a "carbon price-driven" dynamic. In the long term, emphasis should be placed on promoting green hydrogen applications in key scenarios, such as providing purchase subsidies for hydrogen fuel cell heavy-duty trucks, and granting carbon emission reduction rewards to steel enterprises adopting green hydrogen substitution. In the low learning rate (8%) scenario, the absence of effective subsidy policies would delay industrial scaling and postpone the large-scale substitution of green hydrogen by 10–15 years, ultimately affecting the achievement timeline of China's dual-carbon goals.

4.4 Responding to international competition and reshaping industrial patterns

The global hydrogen energy industry is fiercely competitive, with the European Union, the United States, Japan, and South Korea all introducing policies to promote its development. If China fails to promptly introduce effective subsidy policies, it risks losing its first-mover advantage, along with critical market share and technological discourse power.

Implementing subsidy policies during the embryonic stage of hydrogen energy development can help China secure a competitive edge. On the one hand, drawing on the successful model of the wind and solar energy industries, characterized by "domestic subsidies to nurture the industry + international cooperation to expand the market," China can leverage its abundant domestic resources and diverse application scenarios to build scale advantages across the hydrogen energy industrial chain. This would not only reduce costs but also enhance global competitiveness. On the other hand, following the development path of the photovoltaic industry, namely, "subsidies nurturing technology, technology exported globally," subsidy-driven innovation can enable China's hydrogen energy technologies to reach an internationally leading level, creating opportunities for export to emerging markets.

In summary, without initial policy subsidies, reliance solely on spontaneous market regulation would expose enterprises to high costs and risks. As a result, the hydrogen energy industry could fall into a vicious cycle of "small scale–high cost–even smaller scale," repeating the slow early-stage development once experienced by the wind and solar industries before the introduction of subsidy policies.

5 Conclusion

This article systematically reviewed the key experiences of China's wind power and photovoltaic industries in terms of policy guidance, technological innovation, and market cultivation, and applied a benchmarking approach to propose development paths that the hydrogen energy industry can draw upon. Building on the experience that subsidy policies played a crucial role in enabling the rapid take-off of the wind and solar industries, a model for estimating the intensity of hydrogen energy policy subsidies was constructed. Using the learning curve theory, the cumulative installed capacity and the total subsidy scale required to reduce the cost of green hydrogen to 15 yuan/kg were calculated under different learning rate scenarios.

The results indicate that under the benchmark learning rate scenario (18%), the cumulative new installed capacity would be approximately 15.29 GW, with a total subsidy of about 83.4 billion yuan. This represents a feasible pathway for the large-scale development of green hydrogen and a rapid reduction in costs. The study further suggests that, at the current stage, targeted subsidy policies should be implemented to break the initial “high cost–low scale” dilemma, with priority given to supporting the localization of key equipment such as electrolyzers. Additionally, it is essential to improve the supporting systems for green hydrogen standards, strengthen international cooperation mechanisms, and promote the implementation of demonstration projects. Ultimately, through a virtuous cycle of “policy leverage–technological breakthroughs–market expansion,” China’s hydrogen energy industry can achieve high-quality, large-scale development and provide strong support for the realization of the dual-carbon goals.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HoJ: Conceptualization, Data curation, Methodology, Writing – original draft. HiJ: Data curation, Validation, Writing – review and editing. WC: Writing – original draft. JL: Data curation, Formal Analysis, Writing – review and editing. BX: Conceptualization, Funding acquisition, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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