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Research on the innovation and development of China’s hydrogen fuel cell vehicle industry

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RESEARCH ON THE INNOVATION AND DEVELOPMENT OF CHINA’S HYDROGEN FUEL CELL VEHICLE INDUSTRY

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SINGAPORE MANAGEMENT UNIVERSITY

2024

RESEARCH ON THE INNOVATION AND DEVELOPMENT OF CHINA’S HYDROGEN FUEL CELL VEHICLE INDUSTRY

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2024

I hereby declare that this PhD dissertation is my original work

and it has been written by me in its entirety.

I have duly acknowledged all the sources of information

which have been used in this dissertation.

This PhD dissertation has also not been submitted for any degree

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MAY 10TH 2024

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ABSTRACT

China's commitment to achieving "carbon peaking and carbon neutrality" has made the transition from conventional energy sources such as coal, oil, and natural gas to renewable energy sources such as solar, wind, and hydrogen an unavoidable trend. In this regard, the integration of new energy technologies into the automobile and transportation sectors has significantly impacted consumers' lifestyles and has emerged as a key focus for major investment institutions. Lithium-ion batteries, known for their advanced technology, cost-effectiveness, and safety, are the leading choice for use in passenger vehicles, gradually replacing conventional fossil fuel sources. This shift is also contributing to the emergence of a trillion-dollar industry track.

Considering the strategic imperatives of energy diversification and ESG (Environmental, Social, and Governance) considerations, along with the inherent limitations of lithium-ion batteries in terms of low-temperature performance, energy density, and charge/discharge rates, hydrogen fuel cells have rapidly gained traction in automotive transportation, particularly in specific scenarios such as heavy-duty trucks and cold-chain logistics vehicles. There is now an opportunity for hydrogen fuel cells and lithium-ion batteries to form a symbiotic relationship, allowing both systems to leverage their respective technical and cost advantages in different application scenarios.

Historically, both domestic and international research on the hydrogen energy industry has not adequately analyzed the systematic development of hydrogen fuel cell technology, cost reduction pathways, China's energy resource endowment, and relevant industrial policies. This thesis offers a comprehensive analysis of the advancement of hydrogen fuel cells within China's automotive industry by examining and drawing insights from the developmental trajectories of lithium-ion batteries, both at home and abroad, and evaluates the strengths and weaknesses of lithium-ion batteries in contrast to hydrogen fuel cell material systems. This analysis is situated within the broader context of China's strategic positioning within the hydrogen energy industry. Moreover, it draws from real-world applications of hydrogen fuel cells in vehicles, leveraging examples from companies invested in by IDG and practical case studies of hydrogen fuel cell vehicles. Simultaneously, detailed mathematical and theoretical models are utilized to assess the cost reduction pathways within the hydrogen energy industry. The possibility and timeframes for the widespread adoption of hydrogen fuel cells in automotive transportation segments are inferred from these analyses. Additionally, arguments and analyses are presented regarding the advantages between hydrogen fuel cells and lithium-ion batteries in the new energy vehicle market.

This thesis contributes to advancing our understanding of commercializing hydrogen fuel cells in China’s automotive transportation, thereby playing a significant role in promoting the development of China's hydrogen energy industry and influencing investment decisions by institutions in the hydrogen energy sector.

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CHAPTER 1 INTRODUCTION

1.1 Research Background and Research Questions

1.1.1 Background of the Study

During the "14th Five-Year Plan" period, new energy vehicles have emerged as a crucial strategic component of advancing the transformation of the China's energy structure. The utilization of green hydrogen energy and fuel cells will significantly contribute to the development of the new energy industry. The targets of achieving a "carbon peak" by 2030 and "carbon neutrality" by 2060 have spurred transformations in both upstream energy-consuming industries and downstream applications. Clean energy sources such as hydrogen energy and hydrogen fuel cell have emerged as pivotal solutions in this transition. Under the influence of shifting international relations, such as trade conflicts, and domestic policies like "Made in China 2025", there is a notable drive towards manufacturing upgrades in high-tech industries such as hydrogen fuel cell. This momentum is accelerating technological advancements and fostering greater independence and control in these sectors.

Since hydrogen energy was highlighted in the government's work report in 2019, there has been a significant push to implement national support policies aimed at promoting the development and application of technologies related to hydrogen across its entire value chain, including preparation, storage, transportation, refueling, and utilization. Efforts have also been directed towards constructing necessary facilities and services to support these technologies, alongside the formulation and enhancement of relevant standard systems within this sector. Policies related to hydrogen energy and fuel cells are aligned with the strategic direction of "learning from past experiences and promoting high-quality, balanced development across technology, application, and infrastructure." The core principle is to facilitate breakthroughs in critical upstream components and technology, as well as downstream applications and infrastructure development. This approach aims to avoid an overemphasis on policies solely focusing on sales, which could result in a lower-level development of the industry.

In September 2020, the *Notice on Launching Fuel Cell Vehicle Demonstration Projects* jointly issued by five ministries and commissions of China emphasized the importance of focusing on eight core components for technological breakthroughs in upstream key components. In terms of promoting downstream applications, since 2017, various Chinese ministries and commissions have successively issued policies aimed at formulating technical strategies, industrial planning, and demonstration and application programs centered around automotive sectors to drive the development of the hydrogen energy and fuel cell industry. Regarding infrastructure development, in May 2020, the Ministry of Finance of China issued the *Letter on Soliciting Opinions on the <Notice on Launching Fuel Cell Vehicle Demonstration Projects>* (Draft for Opinion), proposing to raise the daily refueling capacity subsidy threshold for new hydrogen refueling stations from "200 kg/day" to "500 kg/day". This adjustment aims to encourage the construction of hydrogen refueling stations.

The utilization of hydrogen energy in automotive transportation sector stands as a pivotal direction within the industrialization of hydrogen energy. In August 2021, the four-year "subsidies with awards" policy for hydrogen fuel cell vehicles officially took effect. Beijing, Shanghai, and Guangdong emerged as the first batch of demonstration cities nationwide, leading the launch of demonstrations and applications of hydrogen fuel cell vehicles. Subsequently, in November, the state unveiled the "14th Five-Year Plan," propelling the industrialization of hydrogen energy to a rapid development phase. Simultaneously, many provinces' local governments have unveiled plans for hydrogen energy and fuel cell vehicle industry, which are paving the way for substantial opportunities to expedite the industrialization of hydrogen energy. Since 2019, provinces and cities such as Beijing, Jiangsu, Guangzhou, Shandong, Inner Mongolia, and Shanghai have issued local industrial policies outlining specific plans for industrial output value, the establishment of enterprises, the deployment of hydrogen fuel cell vehicles, and the development of hydrogen refueling stations. This thesis primarily focuses on the development prospects of hydrogen fuel cells in the automotive transportation sector, assessing their economic viability and commercial feasibility compared to lithium batteries.

1.1.2 Research Questions

The integrity of the industry is a crucial indicator of industrial competitiveness. In recent years, there has been increasing emphasis on ensuring the integrity of the industry within strategic and pillar industries. New energy vehicles represent a critical technical strategy for strengthening China's automobile industry. The transition from conventional fuel vehicles to new energy vehicles is deemed inevitable, and the integrity of supply chain for new energy vehicle plays a pivotal role in determining the success or failure of the automotive industry's strategy to a significant extent.

Hydrogen fuel cell vehicles, serving as a crucial complementary type of new energy vehicles, have experienced rapid growth in production, popularization, and application in China since 2018. In 2019 alone, over 3,000 domestic hydrogen fuel cell commercial vehicles were manufactured, propelling China to the forefront globally in terms of production and deployment of these vehicles. Simultaneously, domestic industries related to hydrogen fuel cell vehicles have accelerated the deployments. Before achieving widespread adoption, it is crucial to conduct a comprehensive analysis of the hydrogen fuel cell vehicle industry supply chain. This involves identifying the strengths and weaknesses of the industry supply chain and strategically targeting key areas for industrial development. Therefore, the aim is to bolster the national competitiveness of the hydrogen fuel cell vehicle industry.

Battery technology innovation plays a crucial role in achieving the goal of "carbon peaking and carbon neutrality" in China's automotive transportation sector, contributing significantly to energy conservation and emission reduction efforts. Compared to lithium-ion batteries, hydrogen fuel cells offer several advantages such as high energy density, excellent performance in low temperatures, and rapid hydrogen refueling. These characteristics make hydrogen fuel cells a promising technology route for new energy vehicles, particularly in specific application scenarios. However, the hydrogen fuel cell industry is currently in its early stages of development, facing challenges such as the need for technology improvement and high upstream costs. Despite the implementation of supportive policies, the economic competitiveness of hydrogen fuel cells still falls short compared to lithium-ion batteries. Continuously improving the key technologies of the hydrogen fuel cell industry, reducing production costs, and promoting commercialization are critical challenges that must be addressed at this stage. These efforts represent the top priority for achieving a widespread adoption of hydrogen energy in automotive transportation.

To address these issues, we delve into the technological advancement and research and development status of key segments within China's hydrogen fuel cell industry. Understanding why certain areas are experiencing stagnation is crucial. Next, we outline strategies for reducing costs and identify the pivotal factors affecting hydrogen fuel cell enterprises. It is essential to compare these factors horizontally with the lithium-ion batteries. Lastly, a comprehensive analysis should weigh the pros and cons of hydrogen fuel cell systems to gauge their viability in automotive transportation.

In summary, this thesis seeks to explore the development prospects of hydrogen fuel cells in automotive transportation and assess their economic and commercial viability relative to lithium batteries. The author intends to employ a wide range of models to analyze the potential growth of hydrogen fuel cells in the new energy vehicle market. The thesis aims to contribute to the debate surrounding the choice between hydrogen fuel cell and lithium battery routes.

1.2 Significance and Innovativeness of the Study

1.2.1 Significance of the Study

The expansion of the domestic hydrogen fuel cell vehicle industry is rapidly advancing, positioning itself as a critical component within the realm of new energy vehicles. Prior to widespread adoption, it is essential to systematically analyze the hydrogen fuel cell automobile industry supply chain, identify its strengths and weaknesses, and pinpoint key areas for industrial development. This approach will bolster the competitiveness of the industry.

The hydrogen fuel cell automobile industry supply chain primarily comprises three main segments: first, upstream activities encompassing hydrogen production, storage, transportation, and refueling; second, midstream operations involving hydrogen fuel cell power systems and critical components; and third, downstream activities focused on vehicle production. When comparing the hydrogen fuel cell automobile industry supply chain to the lithium-ion battery automobile industry supply chain, notable differences primarily emerge in the upstream and midstream sectors. Key changes are centered around enhancing the hydrogen energy industry and advancing technology iterations within the hydrogen fuel cell system. The exploration of hydrogen fuel cell industrialization in China is important in guiding the selection and development of new energy vehicle technical strategies.

Through examining both domestic and international historical documents, the author discovered a relative deficiency in research pertaining to this field. Therefore, the significance of this thesis lies in addressing the research gaps within the related fields, conducting a comprehensive analysis of the hydrogen fuel cell automobile industry, exploring cost reduction strategies for hydrogen fuel cell vehicles through model construction, and presenting a robust argument regarding whether hydrogen fuel cell vehicles could potentially replace or partially replace lithium-ion battery behicles through cost reductions in the future. This thesis aims to establish a reference basis and offer suggestions for future policy directions in hydrogen fuel cell technology within the automotive transportation sector. Additionally, it seeks to provide valuable insights and considerations for advancing hydrogen energy industrialization in China.

1.2.2 Innovation

This thesis has the following three main innovations:

(1) Innovation in the theoretical point of view: The conclusion of this thesis seeks to ascertain the ultimate victor in the technology route competition between hydrogen fuel cells and lithium-ion batteries within the new energy vehicle market. Furthermore, it aims to offer theoretical support on the potential large-scale application of China's hydrogen fuel cell technology in automotive transportation, thereby augmenting research in this field.

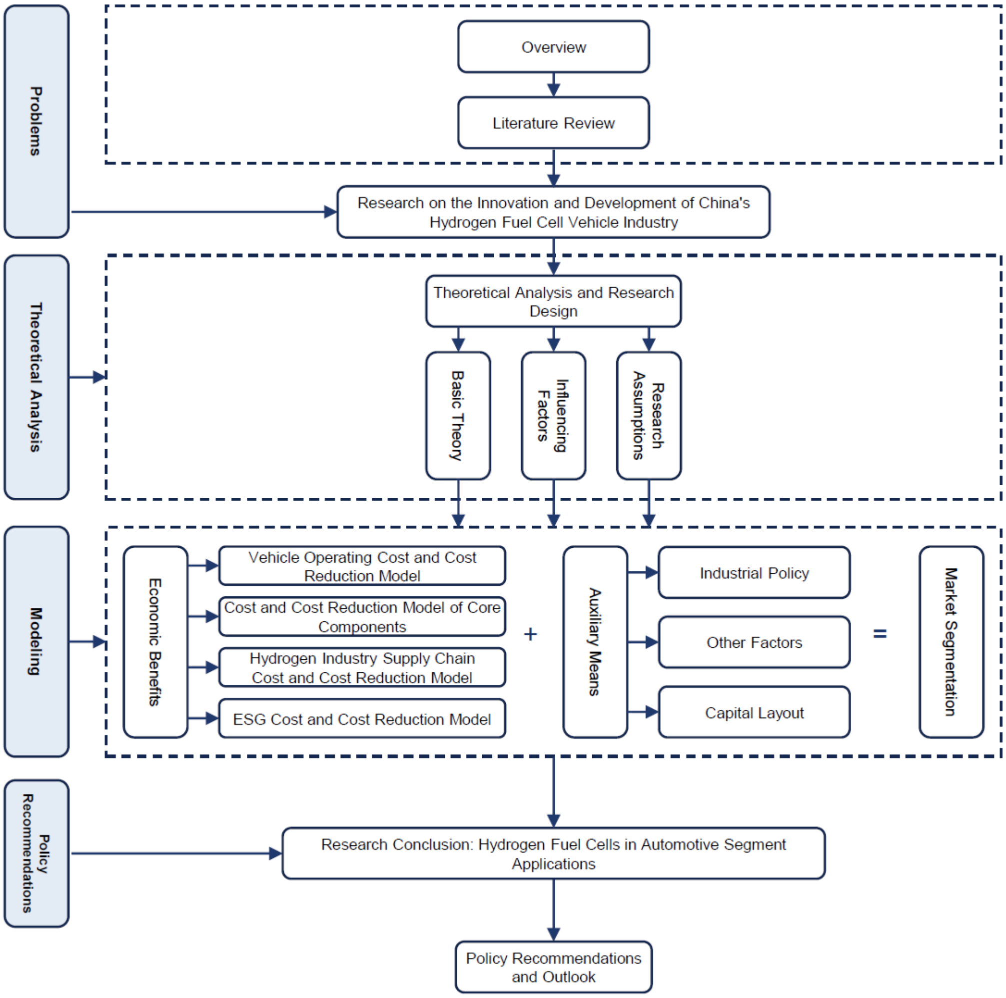
(2) Innovation in research methodology: By leveraging publicly available data and research findings related to China's hydrogen fuel cell industry and incorporating interview insights from IDG Capital's portfolio companies in this sector, this study is innovative in data collection and practical methodology. This approach enables the development of models and predictions for cost reduction pathways, marking a significant advancement in research methodology and application.

(3) Contribution to policy recommendations: This thesis offers valuable insights and references for the policy evolution of China's hydrogen energy and fuel cell industries, along with providing specific recommendations to the selection of new energy vehicle technical strategies.

1.3 Research Technology Roadmap

This thesis examines the industrial development of hydrogen fuel cell vehicles in China. Firstly, by reviewing domestic and international literature, this thesis identifies research gaps and formulates relevant research questions. Secondly, a model is constructed based on the economic principles of new energy vehicles, focusing on comparing Total Cost of Ownership (TCO) and Environmental and Social Governance (ESG) parameters of various new energy vehicles. This model aims to assess the economic viability of hydrogen fuel cell vehicles by analyzing and dissecting different sub-factors that influence their economic benefits. Subsequently, the application direction of hydrogen fuel cells in the automotive sector is comprehensively evaluated, taking into account industrial policies and capital investments to identify key areas for potential growth and breakthroughs. In conclusion, by leveraging the potential application and commercialization of hydrogen fuel cells across different automotive segments, this thesis offers pertinent policy recommendations. Additionally, it presents an outlook on the future development of the hydrogen energy industry, as illustrated in "Fig. 1.3.1 Research Technology Roadmap."

Fig. 1.3.1 Research Technology Roadmap



1.4 Overview and Structural Arrangement of the Research

This thesis is structured into seven chapters. The research content is summarized and organized as follows:

Chapter 1 Introduction: This chapter introduces the research background, outlines the research questions addressed in this thesis, and highlights its significance contributions. China is undergoing a significant shift in energy upgrading and transformation, with the development of the hydrogen energy industry aligning closely with China's strategic imperative for energy diversification and the advancement of renewable and clean energy initiatives under the "carbon peaking and carbon neutrality" policy. Following the inclusion of hydrogen energy in the government report in 2019, there has been a concerted effort to introduce national policies aimed at promoting the continuous advancement of the hydrogen energy industry. Among these efforts, the application of hydrogen fuel cells in the field of automotive transportation stands out as a crucial direction for advancing hydrogen energy industrialization. In August 2021, the national subsidy policy for hydrogen fuel cell vehicles was officially implemented, marking a significant milestone. Subsequently, various regions have released comprehensive plans for the hydrogen energy and fuel cell vehicle industry, propelling the development of hydrogen fuel cell industrialization into a phase of rapid growth. Compared to lithium-ion batteries, hydrogen fuel cells offer several advantages such as high energy density, excellent performance in low temperatures, and rapid hydrogen refueling. These characteristics make hydrogen fuel cells a promising technology route for new energy vehicles, particularly in specific application scenarios. However, the hydrogen fuel cell industry is currently in its early stages of development, and there is a need for significant advancements in technology. This thesis primarily focuses on analyzing the feasibility of applying hydrogen fuel cells in the field of automobile transportation.

Chapter 2 Literature Review: This chapter reviews, organizes, and summarizes the literature and information related to the development of the new energy automobile industry both domestically and internationally. Firstly, through a comprehensive review of the diverse technical strategies, industrial evolution trajectories, and key driving factors influencing the development of lithium-ion batteries, this study focuses on analyzing the developmental processes observed in China, Japan, and South Korea during distinct time periods characterized by their significant market shares. The goal is to establish a foundation that can serve as a reference for promoting and implementing hydrogen fuel cells in the new energy vehicle industry. Secondly, by conducting a literature review on hydrogen energy technical strategies and industry supply chain, this study aims to analyze and compare the strengths and weaknesses of hydrogen fuel cells and lithium-ion battery systems. Additionally, it will integrate China's hydrogen energy industry policies to delineate the technological and industrial development trajectory of hydrogen fuel cells within China. This analysis will be combined with the development path of the lithium battery industry to draw comparisons and insights. Finally, by examining the research gaps identified in the existing literature and aligning them with the objectives set forth in this thesis, we can highlight the core issues that require attention.

Chapter 3 Research Methods and Data Sources: This chapter outlines the primary research methods utilized in this thesis, encompassing literature review, qualitative analysis (comprising survey and case analysis), and quantitative analysis employing mathematical models. Additionally, it elucidates the relevant data sources employed and the methodologies utilized for collecting and organizing information. Firstly, by reviewing, organizing, and summarizing literature and information pertaining to the development of the new energy automobile industry domestically and internationally, the author provides a comprehensive discussion of China's hydrogen fuel cell automobile industry, both historically and in its current state. This involves comparing the advantages and disadvantages of hydrogen fuel cells and lithium-ion batteries, while integrating China's hydrogen energy industry policies to contextualize the findings. Secondly, the author focuses on key components of the hydrogen fuel cell industry supply chain, leveraging the resources of IDG portfolio companies and due diligence firms. They conduct customer interviews to gather insights from the industry, combining this with theoretical knowledge to analyze and synthesize case studies from various companies. Finally, building upon the industry information and company data collected previously, a mathematical model of economic benefits is developed to analyze the feasibility of cost-reduction strategies and market applications for hydrogen fuel cells.

Chapter 4 Model Construction: In this chapter, we develop a mathematical model to assess and compare the economic advantages of automobiles across various technical strategies – conventional fuel, hydrogen fuel, and pure electric vehicles. First, the author builds a model of the vehicle's operating costs (including vehicle selling price and operation and maintenance costs). In this study, the selling price of vehicles is intricately linked to their manufacturing costs, while the operation and maintenance expenses are closely tied to fuel costs. Furthermore, through a detailed analysis of hydrogen fuel cell vehicles and their upstream components (including core parts and the hydrogen industry supply chain), the author developed a cost reduction model to examine the key factors influencing the reduction in costs associated with hydrogen fuel cell vehicles. In this analysis, the core components encompass fuel cells, hydrogen storage systems, and battery systems, and the hydrogen industry supply chain involves processes related to the "preparation, storage, transportation, and refueling" of hydrogen. The technical solutions for various aspects of the hydrogen industry supply chain, particularly in preparation, storage, and transportation, have not yet reached a consensus. Hydrogen production methods include production from coal, natural gas, and water electrolysis. Regarding storage and transportation, options range from using tube trailers for hydrogen transport and hydrogen pipeline transmission to liquid hydrogen tanker storage and transportation. The discussion paves the way for the next chapter for analyzing and predicting feasible hydrogen preparation, storage, and transportation routes in the future. The author achieves this by constructing cost models for different technological solutions for each stage in the hydrogen industry supply chain.

Chapter 5 Key Assumptions and Data Analysis: Building upon the model constructed in the previous chapter, this chapter introduces key assumptions and conducts data analysis of the cost-reduction model associated with hydrogen fuel cell vehicles and their industry supply chain. To thoroughly examine the economics of vehicles across various technical strategies, the model calculations in this dissertation does not incorporate the subsidy factor. Instead, subsidies are solely regarded as a subsequent policy-driven regulation aimed at expediting industry development. Using hydrogen fuel cell heavy-duty trucks as an example, the author computes the cost-reduction trajectory of hydrogen fuel cell vehicles through modeling, then compares these costs with those of conventional fuel vehicles and pure battery vehicles and examines the potential for applying hydrogen fuel cell vehicles in specific fields by integrating the carbon reduction benefits associated with Environmental, Social, and Governance (ESG) considerations. Furthermore, the author conducts cost-reduction calculations using learning curves for both the hydrogen industry supply chain and hydrogen fuel cell vehicles separately. The outcomes from these calculations align with the predictions made by the cost-reduction models for each respective segment. Similarly, the author also models other vehicle application scenarios, including buses, logistics vehicles, and passenger vehicles.

Chapter 6 Application Case Analysis: This chapter examines hydrogen fuel cell vehicles and their upstream industries by presenting practical application cases within the hydrogen fuel cell vehicle industrial chain. The analysis includes case studies such as Jinnan Iron and Steel Park Transportation, GLP Cold-chain logistics Vehicles, and the Sinopec Kuqa Green Hydrogen Project. These cases highlight the characteristics of economically viable application and offer practical support for the theoretical economic model presented in this thesis.

Chapter 7 Research Conclusions and Policy Recommendations: Drawing upon the results from the preceding chapters, this final chapter synthesizes the feasibility and pivotal industrial nodes for hydrogen fuel cell applications in the vehicle sector. This chapter also analyzes other influencing factors and offers relevant suggestions and policy related to the hydrogen energy industry in China.

CHAPTER 2 LITERATURE REVIEW

Firstly, this chapter examines the technological and industrial development paths of lithium-ion batteries, as well as the key factors that drive this progress, by systematically reviewing, organizing, and summarizing existing literature and information pertaining to the development of the new energy vehicle industry both domestically and internationally. Secondly, through an analysis of the strengths and weaknesses of various material systems used in hydrogen and lithium-ion batteries and considering China's hydrogen energy industry policy, this study delineates the technological and industrial development trajectories of hydrogen fuel cells in China. Finally, by analyzing the research gaps and deficiencies identified in historical literature, this thesis aims to summarize the core issues that need to be addressed.

2.1 Research Status of Lithium-ion Battery Industry Development

China's research on lithium batteries commenced in 1982, and as of July 17, 2022, a total of 3,500 relevant papers have been retrieved on China Academic Journals. The number of recent publications has shown a rapid increase, reflecting a growing interest among Chinese scholars in lithium battery research over the past decade.

In 2011, Gao Pengfei and Yang Jun published *Research Progress on Silicon Composite Anode Materials for Lithium-ion Batteries*, discussing the advantages and disadvantages of silicon-based anode materials. They highlighted that silicon-based anode materials are poised to become one of the most promising next-generation materials for lithium-ion batteries in the future.[1]

In 2011, Wu Kai et al. published *Research on the Safety Performance of Lithium-ion Batteries*, emphasizing that the safety of lithium-ion batteries remains a primary factor limiting the expansion of their application fields.[2]

In Jiang Bin's 2011 publication titled *Development Status and Research Progress of Lithium-Ion Battery Cathode Materials*, the advantages and disadvantages of various cathode materials were discussed. It was pointed out that relying solely on lithium cobalt oxide as the cathode material for lithium-ion batteries would no longer be sustainable. Instead, the future development is anticipated to move towards a more diverse and multi-variety direction. Towards the conclusion of the article, it was suggested that ternary materials and lithium iron phosphate would emerge as the preferred choices for the next generation of power batteries.[3]

In 2012, Yang Yong and colleagues published a paper titled *Research Progress on Several Cathode Material Systems for Lithium-Ion Batteries in Science in China*. This paper discussed lithium-rich layered oxides and new polyanionic compounds as promising candidates for the next generation of high-energy lithium-ion battery cathode materials.[4]

In 2013, Xu Rui from the Documentation and Information Center of the Shenyang Institute of Automation, Chinese Academy of Sciences, published a paper titled *Measurement Analysis of Aviation Lithium-ion Batteries Based on ISI Web of Knowledge*. This paper conducted a search for relevant papers on the research of aviation lithium-ion batteries from 1997 to 2012 using the ISI Web of Knowledge. The study analyzed the quantity of research papers and identified research characteristics and trends in this field through quantitative analysis and research mining of papers on aviation lithium-ion batteries, as well as through analysis of invention patents and technical fields.[5]

In 2014, Guan Quan, Li Na, and others from the Qingdao Institute of Science and Technology Information published a paper titled *Analysis of Global Innovation Resources for Lithium Batteries Based on the Orbit Patent Database*. This study utilized the Orbit patent statistics software to analyze various aspects of global lithium battery patents, including the number of patents, country distribution, technical fields, major patent holders, and more. The research aimed to elucidate the current status of lithium battery patents, unveil the distribution and characteristics of global innovation resources in this domain, and offer valuable insights for countries and enterprises in formulating technological strategic plans.[6]

In 2021, Chen Hao from Zhejiang University presented the parallel connection of hydrogen fuel cells and lithium batteries in their doctoral thesis titled *Optimal Management of Fuel Cell/Lithium Battery Hybrid Systems*. This work involved a comparative analysis of four different hybrid system topologies, examining their respective advantages, disadvantages, and suitable usage scenarios. Based on the feasibility of the system structure, a hybrid power system solution was derived to meet practical needs while ensuring cost control. Furthermore, a power distribution strategy employing fuzzy logic control was proposed to achieve real-time energy management of the Fuel Cell/Battery Hybrid Power System (FCBHPS). Finally, for coordinating the power sources in hydrogen fuel cells and lithium batteries within the hybrid power system, an optimization management strategy based on model predictive control was developed. This comprehensive approach aimed to optimize the performance and efficiency of hybrid power systems integrating hydrogen fuel cells and lithium batteries.

In 2022, Lai Chong, Wang Chenghui, and colleagues published *A Review of Implementation Methods Analysis and Performance Comparison for SOC Estimation of Lithium Battery in Energy Storage Science and Technology*. This study examined the factors influencing lithium battery state-of-charge (SOC) estimation and relevant test standards, and conducted a comparative analysis across four key aspects: conventional methods relying on experimental calculations, filtering algorithms utilizing battery models, data-driven machine learning technologies, and hybrid estimation methods combining data and analog approaches. Through this analysis, the study summarized the technical characteristics, implementation processes, applicable conditions, challenges, and advantages associated with each method. Furthermore, it provided a systematic and comprehensive discussion on the research priorities and the current state of application of existing lithium battery SOC estimation technologies. [7]

The author discovered through extensive literature review that scholarly research on lithium batteries primarily centers around advancements in lithium battery anode and cathode materials, as well as research on lithium battery electrolytes and separators. Additionally, scholars in the field also conduct research on lithium battery safety performance and recycling value.

According to research from Statista, nearly a quarter of global carbon dioxide emissions come from transportation, with 80% of these emissions attributed to road traffic. Therefore, reducing emissions from road traffic is crucial, and transitioning from conventional fossil fuels to new energy sources is essential to achieving this goal. With China being one of the world's largest energy consumers and carbon emitters, its focus on energy security and its "carbon peaking and carbon neutrality" policy are driving factors behind the transition from conventional fuel vehicles to new energy vehicles. Currently, lithium-ion batteries are the primary technology route for powering new energy vehicles. According to the IEA report, the rapid adoption and promotion of lithium-ion battery technology in passenger vehicles and other fields is attributed to its relatively high maturity, affordability, and manageable safety compared to other technologies. According to Bloomberg data statistics, the global penetration rate of lithium-ion passenger vehicles reached 7.5% in 2021. It is projected to increase significantly to 30% by 2025, with the penetration rate expected to continue growing rapidly in the coming years. The development of lithium-ion batteries can be divided into three stages. In the late 1990s, Japanese companies gained a significant first-mover advantage in the consumer battery market due to their early entry into this field. Simultaneously, by continuously establishing patents and investing in new technology research and development, these Japanese companies created significant barriers to entry in the industry and monopolized the supply of most of the world's lithium-ion batteries, thus gaining a substantial market share. In the early 21st century, South Korean companies leveraged global supply chain support and continuously optimized their product cost structures to lower costs, thereby reducing the market share previously held by Japanese companies. Around the same period, Chinese companies began entering the lithium battery industry. In the past decade, the Chinese government implemented supportive policies and leveraged increasing downstream demand to rapidly accelerate the development of the lithium-ion battery industry. This concerted effort has propelled China's market share in the global lithium-ion battery industry to grow significantly. As of now, the lithium-ion battery industry has developed into a landscape dominated by China, Japan, and South Korea. Chinese enterprises have notably strengthened their global influence and standing within this industry.

2.2 Research Status of Hydrogen Fuel Cell Industry Development

China's research and development of hydrogen fuel cells began relatively recently, around the year 2000. Research in this area has been relatively limited, particularly in the field of hydrogen fuel cell vehicles, and there are significant deficiencies and gaps in terms of industrialization research, especially within the Chinese market.

In 2000, Wang Yanhui and Wu Diyong from the Dalian Institute of Chemical Physics, Chinese Academy of Sciences, published a paper titled *The Current Status and Development Trend of the Application of Hydrogen Source Technology in PEMFC*. The paper systematically discusses the current status of hydrogen source technology for proton exchange membrane fuel cell (PEMFC) electric vehicles both domestically and internationally, and highlights that a key technology for the development of PEMFC electric vehicles is on-board fuel hydrogen production technology.[8]

In 2019, Liu Haili from the Sinopec Research Institute published a paper titled *Status and Development Trend of Hydrogen Production and Storage*

Technology for Fuel Cell Vehicles. This paper introduces China's hydrogen production technology and compares various methods, including new energy hydrogen production, and also discusses the amount of hydrogen used by hydrogen fuel cell vehicles and compares the advantages and disadvantages of several domestic and foreign on-board hydrogen storage technologies. It is anticipated that by 2025, China will achieve on-board hydrogen storage capacities of around 6.0 kg per tank, operating at a standard pressure of 70 MPa. The estimated system cost is projected to be controlled at 2,000 yuan per kilogram. By 2030, with advancements in gas storage density, the cost could potentially be reduced further to around 1,800 yuan per kilogram.[9]

In 2021, an article titled *Current Development Status and Future Prospects of Hydrogen Fuel Cell Technology* was published in Volume 23, Issue 4 of the journal Engineering Sciences by the Chinese Academy of Engineering. This article focused on hydrogen fuel cell technology systems and provided a comprehensive analysis of research progress and development trends in proton exchange membranes, electrocatalysts, gas diffusion layers, and other membrane electrode assemblies, as well as bipolar plates, system components, and control strategies. It also analyzed the localization rate, system lifespan, power density, manufacturing costs, and other aspects related to hydrogen fuel cell technology development in China. Based on this analysis, the article proposed a development direction for China's hydrogen fuel cell technology systems by the year 2035.[10]

In 2022, Zhang Lixin, Li Jian, and colleagues from the Nanjing Future Energy System Research Institute of Chinese Academy of Sciences published a research review titled *Research Review on Vehicle Fuel Cell Hydrogen*

Supply Systems. The paper introduces three typical hydrogen supply modes for vehicles (direct discharge circulation mode, dead-end mode, and recirculation mode), details the system composition and working principles of each scheme, provides a thorough analysis and summary of the advantages and disadvantages of these hydrogen supply schemes, and discusses the latest research progress and industrialization status of key equipment such as hydrogen circulation pumps and ejectors in the recirculation mode. The research review lays the foundation for future developments in hydrogen fuel cell vehicle hydrogen supply systems and provides recommendations for their advancement. [11]

In recent years, China's basic research on hydrogen fuel cell technology has become more active, and in certain technical areas, it has demonstrated the potential to reach a level comparable to developed countries. However, overall, China's mastery of core technology and the development of a comprehensive technological system in hydrogen fuel cell technology still lag behind leading nations. For instance, China's first hydrogen fuel cell invention patent only appeared in 1998, and the number of relevant core patents represents only about 1% of the global total. The development of hydrogen fuel cell systems, components, control technology, electrodes, and related areas in advanced countries is relatively well-balanced. Some international enterprises hold leading positions globally in hydrogen fuel cell systems, battery components and processing, control technology, and other critical aspects.

As an emerging clean energy source, hydrogen energy has garnered strategic consensus in the planning of the international community and major countries.[12] The Hydrogen Council considers hydrogen energy to be a crucial starting point for transitioning to cleaner energy sources to help control global warming and limit temperature increases to 2°C. It is predicted that by 2050, hydrogen energy will account for 18% of the global final energy demand, playing a significant role in achieving deep decarbonization across various sectors including transportation, chemical production, industrial energy, building heating, and power generation. This shift to hydrogen energy is expected to result in a reduction of 6 billion tons of carbon dioxide emissions and the consumption and storage of 500 TWh of electricity, which will facilitate the large-scale deployment of renewable energy sources.[13]

Considering China's national circumstances as the world's largest carbon emitter, and with the target of achieving a "carbon peak" by 2030 and "carbon neutrality" by 2060, the promotion and adoption of hydrogen energy offer several advantages. On one hand, promoting hydrogen energy aligns with the Environmental, Social, and Governance (ESG) concept. On the other hand, it helps reduce China's reliance on fossil fuels, which is strategically important for China's energy development goals.

In the realm of automotive transportation, hydrogen fuel cells present a compelling alternative to lithium-ion batteries. With superior energy density, rapid energy delivery, and enhanced performance in low temperatures, they hold the potential to supplant lithium-ion batteries in certain automotive sectors. This positions hydrogen fuel cells as a leading technical strategy in the new energy vehicle landscape.

Based on different technical strategies, hydrogen fuel cells can be categorized into several types. These include acidic fuel cells, alkaline fuel cells (AFC), solid oxide fuel cells (SOFC), and molten carbonate fuel cells (MCFC). Acidic fuel cells further subdivide into proton exchange membrane fuel cells (PEMFC), direct alcohol fuel cells (DAFC), and phosphoric acid fuel cells (PAFC), based on the type of conductive ions utilized. PEMFC currently represents the leading technology for hydrogen fuel cell vehicles, offering a range of significant advantages. These include high power density, lightweight design, compact size, extended lifespan, low operating temperatures, quick startup capabilities, and a well-developed technological foundation. The term "hydrogen fuel cell" as used in this paper refers both qualitatively and quantitatively specifically to the PEMFC (Proton Exchange Membrane Fuel Cell) technology.[14-16]

Several studies indicate that hydrogen fuel cell vehicles are anticipated to have a significant impact on medium and heavy-duty trucks, as well as long-distance road transportation.[17] Nevertheless, the advancement of hydrogen fuel cell technology is still in its nascent stages within the industry. It is imperative to enhance and develop both the technological maturity and the integrity of the industrial supply chain. According to other literature, the commercialization of hydrogen fuel cell vehicles significantly lags behind that of lithium-ion battery vehicles, and the progress in developing supporting infrastructure has been slow. Given the rapid advancements in lithium-ion battery fast-charging technology, the widespread deployment of charging networks, and the ongoing reduction in vehicle costs, it appears unlikely that hydrogen fuel cell vehicles will achieve widespread adoption in comparison.[18, 19]

2.3 Literature Review

Through extensive literature research, the author has analyzed the evolution of lithium-ion battery development across different temporal and spatial dimensions, and has examined and evaluated the global technical strategies and developmental phases of hydrogen fuel cells. The author asserts that prevailing discussions regarding the application of hydrogen fuel cells in the automotive sector, both domestically and internationally, are predominantly shaped by acknowledgment of the current level of commercialization achieved by lithium-ion battery vehicles. This includes factors such as high technological maturity, adequate supporting infrastructure, and favorable economic viability. Additionally, these discussions are informed by forecasts of future technological advancements, such as continuous improvements in energy density and the advancement of fast-charging technology. In this context, two deviations can be observed. Firstly, there is an overestimation of the rate of technological advancement in lithium-ion batteries. Secondly, there is a tendency to overlook inherent performance bottlenecks of the materials used, such as issues related to low-temperature performance.[20, 21]

Meanwhile, the author noted that historical discussions were predominantly centered on overseas markets and lacked a profound understanding of the Chinese market. There was also a deficiency in conducting detailed analyses based on the actual conditions of China's automobile industry, including factors such as China's vehicle operation policies. This limited perspective fails to recognize the significant strategic importance of developing hydrogen energy within the context of China's energy resource distribution, characterized by abundant coal, limited oil, and scarce natural gas. Moreover, the discussions often overlook the potential impact of the growing Chinese hydrogen fuel cell vehicle market on the global hydrogen fuel cell vehicle sector and the broader hydrogen energy industry. [18, 22]

In light of these observations, this thesis aims to comprehensively assess the comparative advantages offered by the material system of hydrogen fuel cells. Furthermore, through theoretical analysis, this thesis will identify the key factors influencing the economic viability of hydrogen fuel cells. By employing mathematical modeling, it aims to predict the cost-reduction trajectory of hydrogen fuel cell vehicles in the Chinese market. Subsequently, the economic benefits of hydrogen fuel cells will be compared with those of conventional fuel vehicles and pure electric vehicles to assess their potential applications in the automotive sector.

In summary, the author contends that this study addresses the deficiencies and gaps identified in historical literature concerning hydrogen fuel cell vehicles, particularly with regard to the industrialization of the Chinese market. The study aims to offer guidance and serve as a reference point for advancing the global hydrogen industry supply chain and shaping related policies.

CHAPTER 3 RESEARCH METHOD AND DATA SOURCES

3.1 Research Methodology

This chapter will describe the primary research methods employed during the dissertation research process, including:

(1) Literature research method: Through reviewing, organizing, and comparing domestic and international literature and information on the innovation and development of the hydrogen fuel cell and lithium battery automobile industries, and by integrating China's hydrogen-related industrial policies, this study aims to achieve an in-depth understanding of the history and current state of China's hydrogen fuel cell automobile industry.

(2) Qualitative analysis method: Gathering primary data by conducting interviews with IDG investee companies and researching various companies, consolidating insights from these cases, and formulating conclusions based on the collected information. Firstly, through the survey method, specifically by conducting interviews with IDG Capital's portfolio companies and research enterprises in the hydrogen energy field, this research aims to systematically gather background information, operational data, factors influencing decision-making, and execution methods of these relevant enterprises. The collected data will be summarized, compared, and analyzed to formulate comprehensive conclusions. Secondly, the case analysis method will be applied to classify and characterize the collected data from the interviews. This

approach involves combining the empirical data with relevant theories to develop representative and detailed enterprise case analyses.

(3) Quantitative analysis method: After obtaining the data from IDG portfolio companies and research entities, relevant industry data from both upstream and downstream sectors of the industry supply chain will be collected, along with macroeconomic data. These datasets will be carefully matched and analyzed. Enterprise data will be processed and organized using ratio analysis, mathematical modeling, trend analysis, structural analysis, mutual comparison, and other methods. Useful information and conclusions will be obtained through these processes, and empirical analysis on the potential cost reductions of hydrogen fuel cells will be carried out.

3.2 Data Sources

This study predominantly relies on firsthand data obtained through research and interviews with enterprises, supplemented by comprehensive industry-related data and information:

(1) Research data: To ensure the fairness and confidentiality of the data obtained from IDG portfolio companies and due diligence enterprises, the company names will be encoded or anonymized in the thesis.

(2) Industry information: Public information and industry experience related to hydrogen energy and fuel cell technology were collected and integrated for this study.

CHAPTER 4 MODELING FRAMEWORK

The economy is a critical indicator for assessing the potential for widespread adoption of hydrogen fuel cell vehicles. At present, the hydrogen energy industry supply chain is still in its early stages, with the upstream "preparation, storage, transportation, and refueling" supporting facilities having yet to reach maturity. Meanwhile, the application scenarios and routes for commercial vehicles are relatively limited, making them more promising candidates to kick off production compared to passenger vehicles. This thesis focuses on modeling the application scenarios of various vehicles and thoroughly discusses them.

Firstly, the author developed a mathematical model to horizontally compare the operating costs of various vehicle types (such as buses, logistics vehicles, heavy-duty trucks, and passenger vehicles) across different technological routes (hydrogen, conventional fuel, and pure electric) at the present time. This approach allows them to determine the operating costs of hydrogen fuel cell vehicles and how they compare with those of conventional fuel vehicles or pure electric vehicles at parity.

Secondly, the author distills the key factors influencing the operational expenses of hydrogen fuel cell vehicles and develops various models for reducing costs. These models analyze strategies for reducing costs at critical points along the industry supply chain. This includes examining changes in costs associated with fuel cell systems and supporting components that impact vehicle selling prices, as well as assessing the influence of hydrogen supply chain costs (covering preparation, storage, transportation, and refueling) to determine the feasibility of achieving cost parity for hydrogen fuel cell vehicles through a strategic reduction pathway.

If the model of this thesis indicates that the final operating cost of hydrogen fuel cell vehicles is projected to reach parity with that of conventional fuel vehicles or pure electric vehicles in a specific vehicle application scenario (such as buses, logistic vehicles, heavy-duty trucks, and passenger vehicles), it is anticipated that hydrogen fuel cell vehicles will lead the way in initiating production in that particular scenario, and vice visa.

It is important to note that, for a comprehensive examination of the economics and cost-reduction trajectories of various technical strategies (hydrogen, conventional fuel, and pure electric), this thesis excludes consideration of policy subsidies in all models. Policy subsidies are solely regarded as a regulator to expedite the attainment of parity when hydrogen fuel cell vehicles are anticipated to achieve final parity in a specific application scenario (such as buses, logistic vehicles, heavy-duty trucks, and passenger vehicles).

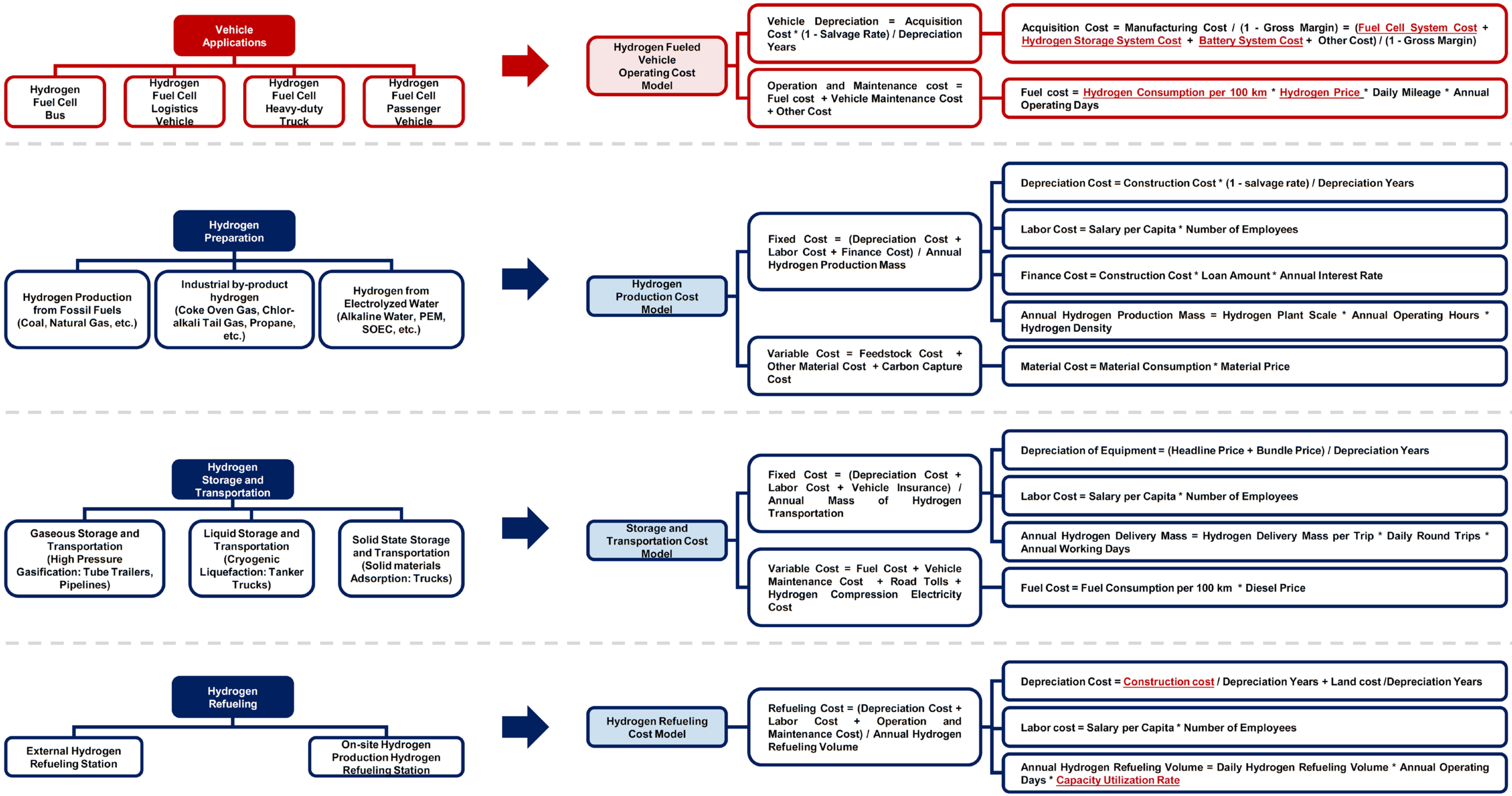
In summary, this chapter elaborates on the operating cost model of hydrogen fuel cell vehicles and its framework for cost reduction and also outlines the cost model and reduction framework for the core components of vehicles and the upstream hydrogen industry supply chain encompassing "preparation-storage-transportation-refueling" and provides definitions of relevant formulas accordingly.

4.1 Vehicle Operating Cost and Cost Reduction Model Framework

The vehicle operating cost model is central to this thesis, serving as the primary tool for comparing and evaluating the economic performance of vehicles using different technologies—hydrogen fuel cell, conventional fuel, and pure electric—across various applications, including buses, logistics vehicles, heavy-duty trucks, and passenger vehicles. Vehicle operating costs can be broken down into vehicle depreciation and operations and maintenance (O&M) costs. Vehicle depreciation is influenced by the selling price of the vehicle, which reflects manufacturing costs and profit margins, as well as subsidies. On the other hand, O&M costs are shaped by factors such as fuel costs, which depend on energy prices, energy consumption, mileage, and days in operation, along with vehicle maintenance expenses.

Hydrogen fuel cell vehicles are currently in the early stages of industrialization, offering significant potential for cost reductions as the technology matures. The manufacturing cost is a critical determinant in reducing the acquisition cost of hydrogen fuel cell vehicles, with significant portions attributable to the costs of the fuel cell system, hydrogen storage system, and battery system. These components are central to the main avenues for cost reduction. Additionally, the hydrogen muzzle price, influenced by the upstream aspects of the hydrogen industry—namely "preparation, storage and transportation, and refueling"—is another crucial factor in the cost-reduction trajectory. Furthermore, the hydrogen consumption per 100 km is identified as a primary factor influencing the O&M costs, as illustrated in "Fig. 4.1.1 Hydrogen Industry Supply Chain and Model Framework."

Fig. 4.1.1 Hydrogen Industry Supply Chain and Modeling Framework



To summarize, the operating cost of a vehicle and its cost reduction path can be expressed by the following formula, where the key factors affecting cost reduction are underlined:

Running Cost = Vehicle Selling Price + O&M Cost = (Manufacturing Cost + Vehicle Sales Profit) + (Fuel Costs + Vehicle Maintenance Fees + Other Costs) = (Fuel Cell Costs + Hydrogen Storage System Costs + Battery System Costs + Other Costs) + Vehicle Sales Profit (Hydrogen Terminal Selling Price * Hydrogen Consumption per 100 km * Daily Driving Mileage * Yearly Operating Days) +Vehicle Maintenance Fees +Other Costs

Operating Cost Reduction = Vehicle Selling Price Cost Reduction + Operation and Maintenance Cost Reduction = (Vehicle selling price - Manufacturing Cost Reduction) + (Fuel Cost Reduction + Vehicle Maintenance Fee + Other costs) = Vehicle Selling Price - (Fuel Cell Cost Reduction + Hydrogen Storage System Cost Reduction + Battery Storage System Cost Reduction) + (Hydrogen Terminal Selling Price Cost Reduction * Hydrogen Consumption Reduction per 100 km * Daily Driving Mileage * Annual Operating Days) + Vehicle Maintenance Fee + Other Costs)

4.2 Core Component Cost and Cost Reduction Model Framework

The operating costs and cost-reduction strategies for hydrogen fuel cell vehicles are closely tied to the costs and pathways for reducing costs of their core and supporting components, particularly the fuel cell system. This thesis delves into the cost components of these core components of hydrogen fuel cell vehicles and develops a model to ascertain if the manufacturing costs of hydrogen fuel cell vehicles can be brought down to a viable price range. This, in turn, would enable hydrogen fuel cell vehicles to compete economically with conventional fuel vehicles and pure electric vehicles in specific niche application scenarios.

Since the fuel cell system (comprising over 50% of the cost), hydrogen storage system (accounting for 10-15% of the cost), and battery system (making up 5-10% of the cost) represent significant portions of the total cost of hydrogen fuel cell vehicles, they constitute the primary avenues for reducing manufacturing costs. Among these components, the electric stack stands out as the cornerstone of the fuel cell system, currently representing over 50% of the system cost. Its core constituents encompass membrane electrodes, which comprise a proton exchange membrane, catalyst, and gas diffusion layer, along with bipolar plates. The author asserts that scaling up the mass production of electro stacks and systems, along with localizing and substituting core components of electrostacks, are pivotal for reducing the cost of fuel cell systems.

According to calculations by the U.S. Department of Energy (DOE), at an annual production scale of 1,000 sets, the system cost is $175/kW, with the electrostack cost at $115/kW. However, when the annual production scale increases to 10,000 sets, the system cost and the electrostack cost decrease significantly to $50/kW and $25/kW, respectively. This substantial reduction underscores the scaling effect inherent in process manufacturing and materials.

At present, China has achieved mass production of systems and electrostack that meet the performance requirements for loaded vehicles. The power of these electrostacks is largely comparable to international standards and, in some cases, even catching up. While membrane electrodes have also achieved mass production at an internationally leading level, other core components still rely on imports. Domestic technology is expected to make breakthroughs in the following areas: 1) Proton Exchange Membrane: These membranes require chemical stability, high mechanical strength, high conductivity, and durability. Products from leading companies like DuPont in the United States, Solvay in Belgium, and Toray in Japan demonstrate superior performance. Domestic enterprises, such as Dongyue, are in the small-batch production stage and still need to undergo testing for wider application, with other companies in the industry relying on imports; 2) Catalysts: Platinum catalysts are predominantly used, but due to resource and cost constraints, there is a need for low platinum loading and high catalytic activity. Domestic enterprises, like H-RISE, have begun mass production capabilities, but many other companies in the industry still rely on imports; 3) Gas Diffusion Layer: This layer is typically based on porous carbon fiber paper or carbon fiber cloth and requires high mechanical strength, suitable pore size, good conductivity, and high stability to facilitate gas and water transmission. Domestic products are in the validation stage, with companies like Shanghai Jazz Material , but largely dependent on imports; 4) Bipolar Plate: The challenge lies in the mass production process. While foreign graphite plates are common, domestic focus is shifting towards metal plates. Metal plate products using mature stamping technology have been localized, emphasizing strength and reliability; 5) Hydrogen Storage Cylinders: These cylinders need to be high-pressure, lightweight, and high-strength, considering hydrogen storage density and the hydrogen embrittlement phenomena. Main types include type III cylinders (metal liners with fiber winding) and type IV cylinders (non-metallic liners with fiber winding). In China, 35 MPa type III cylinders have been successfully implemented for onboard use, while 70 MPa high-pressure type IV cylinders are still dependent on imports.

In summary, this thesis forecasts the manufacturing cost and outlines the cost reduction pathway for hydrogen fuel cell vehicles, leveraging current prices of core components such as the fuel cell system, hydrogen storage system, and battery system. Additionally, it establishes a reasonable annual average reduction rate to guide the cost-reduction efforts effectively.

4.3 Hydrogen Industry Supply Chain Cost and Cost Reduction Model Framework

The operating cost and cost-reduction strategies of hydrogen-fueled vehicles are partly dependent on the cost and cost-reduction strategies of hydrogen sources. This thesis analyzes the cost components of each stage of the hydrogen upstream industry supply chain "preparation, storage, transportation, and refueling" and builds a relevant model to determine whether the terminal price of hydrogen can be reduced to a reasonable price range, so that hydrogen fuel cell vehicles can be economically competitive with conventional fuel vehicles and pure electric vehicles in specific applications.

4.3.1 Hydrogen Production Cost Model Framework

According to the *2020 White paper on China's Hydrogen Energy and Fuel Cell Industry* report, there are currently three mainstream paths for hydrogen preparation: 1) Hydrogen Production from Fossil Fuels: This method can be further divided into hydrogen production from coal and hydrogen production from natural gas, depending on the choice of raw materials. While this strategy is technologically mature with a high yield and low cost, it involves a long process and results in significant carbon emissions; 2) Industrial By-Production of Hydrogen: The initial investment for this approach is relatively smaller, and the energy consumption is lower compared to coal-based hydrogen production methods. However, the construction scope is constrained by the availability of raw materials, and there are regional disparities in distribution; 3) Hydrogen Production From Electrolysis Of Water: This method, depending on the technical route, can be divided into alkaline (ALK), proton exchange membrane (PEM), and solid oxide (SOEC) electrolysis of water to produce hydrogen, among others. While this strategy involves simple equipment and stable operation, it has higher energy consumption, and the current cost of hydrogen production is higher.

Different hydrogen production processes and technological levels lead to variations in hydrogen preparation costs and purity. Given China's energy cost and resource endowments, coal resources are abundant and widely dispersed, with mature coal-based hydrogen production technology serving as the predominant source of hydrogen in the country. Industrial by-product hydrogen serves as a valuable complement to China's current hydrogen sources, but there are significant regional variations in the distribution of the chemical industry in the country. For instance, coking predominates in East and North China, while chlor-alkali is concentrated in Xinjiang, Shandong, Inner Mongolia, and Hebei. Synthesis ammonia/alcohol production is centered in Shandong, Shanxi, and Henan, leading to a dispersed hydrogen source with divergent cost structures. Presently, water electrolysis for hydrogen production is in its nascent stages, with alkaline water electrolysis representing the most mature technology and offering lower production costs. Proton exchange membrane (PEM) electrolysis boasts a simple process and rapid start-up and shutdown speeds, rendering it better suited for accommodating the fluctuating nature of renewable energy sources. However, its reliance on precious metal catalysts contributes to higher production costs. Solid oxide electrolysis cell (SOEC) technology demonstrates the highest theoretical energy efficiency, albeit its developmental stage remains in research and development, far from being ready for commercialization. The author believes that the heart of reducing electrolytic hydrogen production costs lies in electricity prices, electrolyzer costs, and efficiency (including power consumption). Future integration with inexpensive wind power resources is poised to expedite the adoption of green hydrogen, gradually supplanting gray and blue hydrogen.[23-26]

In summary, the author will analyze the cost models for hydrogen production from fossil fuels (coal and natural gas) as well as from electrolysis methods using alkaline and PEM (Proton Exchange Membrane) technologies.

1) Hydrogen Production from Conventional Fossil Fuels

The unit cost of hydrogen production from coal and natural gas comprises fixed costs and variable costs. Fixed costs encompass depreciation expenses (linked to construction costs, depreciation period, annual maintenance costs, and residual value rates), labor expenses (including per capita salary and number of employees), and financial expenses (associated with loan amount and annual interest rate). Variable costs consist of raw material expenses (coal or natural gas costs, depending on raw material consumption and prices), additional material costs (for coal-to-hydrogen production, including oxygen costs and auxiliary material costs; for natural gas hydrogen production, auxiliary material costs are considered; dependent on material consumption and prices), and fuel power expenses (for hydrogen production from coal, encompassing electricity costs, circulating water costs, fresh water costs, desalinated water costs; for natural gas hydrogen production, covering electricity costs, circulating water costs, fresh water costs, desalinated water costs, steam costs, and fuel gas costs; influenced by fuel consumption and prices). Moreover, the annual hydrogen production scale of the equipment (along with the scale of the hydrogen production unit and related years of operation) also impacts the unit cost. Additionally, the cost of carbon capture, which is influenced by carbon emissions and the price of carbon capture, is a significant factor affecting the cost of hydrogen production.

In summary, the unit cost of hydrogen production from coal and natural gas can each be represented by the following formulas:

Unit cost of hydrogen production from coal = Fixed Cost + Variable Cost = (Depreciation Cost + Labor Cost + Finance Cost) + (Cost of Coal + Cost Of Other Materials + Fuel And Power Cost) + Carbon Capture Cost = [(Construction Cost * (1 - Salvage Rate) + Construction Cost * Annual Repair

Cost * Depreciation Life)/Depreciation Life + (Salary Per Capita * No. of Employees) + (Construction Cost * Loan Amount * Interest Rate Per Annum)]/ Annual Scale of Hydrogen Production + (Coal Consumption * Coal Price) + (Oxygen Consumption * Oxygen Price) + (Auxiliary Material Consumption * Auxiliary Material Price) + (Electricity Consumption * Electricity Price) + (Recycled Water Consumption * Recycled Water Price) + (Fresh Water Consumption * Fresh Water Price) + (Demineralized Water Consumption * Demineralized Water Price) + (Carbon Emissions Per Unit * Carbon Capture Price); Annual Scale of Hydrogen Production = Scale Of Hydrogen Production Plant * Annual Operating Hours

Unit cost of hydrogen production from natural gas = Fixed Cost + Variable Cost = (Depreciation Cost + Labor Cost + Finance Cost) + (Cost Of Natural Gas + Other Material Cost + Fuel Power Cost) + Carbon Capture Cost = [(Construction Cost * (1 - Salvage Rate) + Construction Cost * Annual Repair Cost * Depreciation Life)/Depreciation Life + (Salary Per Capita * No. of Employees) + (Construction Cost * Loan Amount * Interest Rate)]/Annual Scale of Hydrogen Production + (Salary Per Capita * No. of Employees) + (Unit Consumption of Natural Gas * Natural Gas Price) + (Unit Consumption of Auxiliary Materials * Auxiliary Material Price) + (Unit Consumption of Electricity * Electricity Price) + (Unit Consumption of Recycled Water * Recycled Water Price) + (Unit Consumption of Fresh Water * Fresh Water Price) + (Unit Consumption of Demineralized Water * Demineralized Water Price) + (Unit Carbon Emission * Carbon Capture Price) + (Unit Consumption Of Steam * Steam Price) + (Unit Consumption Of Fuel Gas * Fuel Gas Price) + (Unit Carbon Emission * Carbon Capture Price); Annual Hydrogen

Production Scale = Scale Of Hydrogen Production Plant * Annual Operating Hours

2) Hydrogen Production from Electrolyzed Water

For alkaline water and PEM hydrogen production, the unit cost of hydrogen production comprises fixed and variable costs. Fixed costs encompass depreciation (tied to equipment investment, civil construction, equipment installation, depreciation period, and salvage rate), labor costs (related to per capita salary and number of employees), operation and maintenance costs (associated with equipment investment), and financial costs (linked to the loan amount and annual interest rate). Variable costs include electrolysis costs (dependent on electricity consumption and electricity price) and other material costs (for alkaline water hydrogen production, this includes the costs of pure water, cooling water, and KOH; for PEM hydrogen production, this involves costs for pure water and cooling water, related to material consumption and material price). Additionally, these costs are influenced by the annual hydrogen production capacity of the facility, which depends on the size of the hydrogen production unit and its annual operational hours.

In summary, the unit cost of hydrogen production from alkaline water and from PEM can each be represented by the following formulas:

Unit cost of alkaline water hydrogen production = Fixed cost + Variable cost = (Depreciation cost + Labor cost + Finance cost) (Electricity cost + Other material cost) = [(Equipment Investment + Civil Construction And Equipment Installation)/Depreciation Life + (Salary Per Capita * No. of

Employees) (Construction Cost * Loan Amount * Interest Rate Per Annum)]/Annual Scale of Hydrogen Production (Electricity Consumption * Electricity Price) + (Pure Water Consumption * Pure Water Price) + (Cooling Water Consumption * Cooling Water Price) + (Consumption Per Unit of KOH * Price Of KOH); Annual Scale Of Hydrogen Production = Scale Of Hydrogen Production Plant * Annual Operating Hours

Unit cost of PEM hydrogen production = Fixed Cost + Variable Cost = (Depreciation Cost + Labor Cost + Finance Cost) (Electricity Cost + Other Material Cost) = [(Equipment Investment + Civil Construction and Equipment Installation)/Depreciation Life + (Salary Per Capita * No. of Employees) + (Civil Construction Cost * Loan Amount * Interest Rate Per Year)]/Annual Scale Of Hydrogen Production + (Electricity Consumption * Electricity Price) + (Pure Water Consumption * Pure Water Price) + (Cooling Water Unit Consumption * Cooling Water Price); Scale of Hydrogen Production Plant * Annual Operating Hours

4.3.2 Storage and Transportation Cost Modeling Framework

The produced hydrogen must be stored and transported to its final destination. This process can be categorized into three forms based on the state of hydrogen: gas, liquid, and solid. 1) Gas storage and transportation: Involve using tube trailers or pipelines to transport gaseous hydrogen. The former method employs high-pressure technology (working pressure of 20-50 MPa), which results in high energy consumption but offers a hydrogen transportation capacity of 250-460 kg per vehicle. This approach is suitable for small-scale and short-distance scenarios, with mature technology that has been widely adopted. On the other hand, the latter method uses low-pressure technology (working pressure of 1-4 MPa), leading to lower energy consumption but requiring higher fixed investment. It provides a hydrogen transportation capacity of 310-8,900 kg per hour, making it suitable for large-scale and long-distance scenarios. However, this technology has not been widely adopted in China, and caution should be exercised to avoid the "hydrogen embrittlement" phenomenon. 2) Liquid storage and transportation: Liquid hydrogen can be transported using tanker trucks or organic carriers. The former method involves using low temperatures to liquefy hydrogen, resulting in a hydrogen capacity of 360-4,300 kg per tanker truck. While this approach boasts higher storage and transportation efficiency compared to the gaseous method, it incurs higher energy consumption and costs for liquefaction, along with increased equipment requirements. This method is predominantly utilized in the military industry domestically. The latter method, with a capacity of 2,600 kg per vehicle, involves reacting hydrogen with organic matter to facilitate "storage-transportation-release". Currently, this method is in the stage of technological research and development. However, the process of "hydrogenation-dehydrogenation" results in less pure hydrogen, and this method has not yet been widely implemented on a large scale. 3) Solid-state storage and transportation: This entails adsorbing hydrogen in solid materials for transportation using hydrogen-storage metals. With a hydrogen transport capacity of 24,000 kg per vehicle, this method offers convenient transportation and excellent safety. However, it is still in the stage of technological development and has not been widely applied on a large scale (refer to "Fig.

4.3.2.1 Comparison of Hydrogen Storage and Transportation Strategy" for details.)[27]

In China, hydrogen storage and transportation are primarily conducted through tube trailers. However, technologies for pipeline hydrogen transmission and liquid hydrogen tanker truck transportation are expected to mature gradually in the future. In summary, the author will analyze the cost model for these three transportation strategies.

Fig. 4.3.2.1 Comparison of Hydrogen Storage and Transportation Strategies

Mode of Storage and Transportation		Range of Transportation Volume	Application	Advantages and Disadvantages
Gaseous	Tube Trailer	250-460kg/vehicle	- Widely used	- Mature technology, suitable for small-scale, short-distance transportation
	Pipeline	310-8,900kg/h	- Limited use overseas but has not yet gained popularity domestically	- Increased fixed investment, ideal for extensive, long-distance transportation
Liquid	Tanker	360-4,300kg/vehicle	- Widely used abroad, the domestic military industry plays a primary role.	- Liquefaction requires significant energy consumption and incurs high costs due to extensive equipment requirements
	Organic Carrier	2,600kg/vehicle	- Experimental stage, few applications	-Hydrogenation-dehydrogenation processes often result in low hydrogen purity
Solid State	Hydrogen Storage Metal	24,000kg/vehicle	- Experimental stage, few applications	- Easy and safe transportation

1) Tube Trailer Transportation of Hydrogen

Tube trailer transportation of hydrogen is currently the most developed method for storing and transporting hydrogen. This method is well-suited for short-distance transportation, typically within a radius of 200 kilometers.

The unit cost of tube trailer transportation of hydrogen comprises fixed and variable costs. Fixed costs include equipment depreciation (linked to headstock price, harness price, and the depreciation period), labor costs (related to per capita salary and the number of employees), vehicle insurance, and variable costs include fuel costs (related to fuel consumption per 100 km and the price of diesel fuel), vehicle maintenance fees, road tolls, and the cost of compressed hydrogen electricity (related to compressed hydrogen electricity consumption and the electricity price). These costs are also influenced by the trailer's annual hydrogen transportation quantity (related to the quantity of a single transportation, the number of round-trips per day, and the number of days of annual operation).

Among these factors, the cost of tube trailer transportation of hydrogen is primarily influenced by the distance from the hydrogen source and the working pressure (which is positively correlated with the annual hydrogen quantity). Conversely, there is limited potential for cost reduction in other segments of the transportation process.

In summary, the unit cost of tube trailer transportation of hydrogen can be expressed by the following formulas, where the value of the number of daily round trips of the trailer is rounded down:

Unit cost of tube trailer transportation of hydrogen = Fixed Cost + Variable Cost = (Depreciation of Equipment + Labor Cost + Vehicle Insurance) + (Fuel Cost + Vehicle Insurance Cost + Road Tolls + Compressed Hydrogen Electricity) = [(Headstock Price + Harness Price)/Depreciation Life (Salary Per Capita * No. of Employees) + Vehicle Insurance Cost (Fuel Consumption Per 100 km * Price of Diesel) + Vehicle Maintenance Cost + Road Tolls + (Compressed Hydrogen Electricity Consumption * Price of Electricity)]/Annual Hydrogen Mass; Annual Hydrogen Mass = Mass of Hydrogen Transported Per Trip * Number of Round Trips Per Day * Number of Working Days Per Year = Trailer Loading Capacity * (1 - Harness Hydrogen Residual Rate) * Working Hours Per Day/(Distance To Hydrogen

Source/Average Speed of Trailer * 2 + Hours Of Refueling And Unloading Hydrogen In Trailer) * The Number of Days Of Annual Operation

2) Pipeline Hydrogen Transportation

Pipeline hydrogen transportation is suitable for large-scale and long-distance transportation. In order to prevent "hydrogen embrittlement," pure hydrogen pipelines must be constructed from low carbon steel, which results in a cost that is more than twice that of natural gas pipelines. This lack of cost advantage poses a challenge for hydrogen pipeline infrastructure development. Currently, existing natural gas pipelines are utilized overseas to blend and transport 15-20% hydrogen with natural gas. However, challenges such as separation technology and hydrogen leakage persist, keeping pipeline hydrogen transmission in the experimental stage.[28]

The cost of pipeline hydrogen transportation comprises fixed and variable components. Fixed costs encompass pipeline depreciation (linked to total investment, hydrogen loss rate during transport, and pipeline lifespan), as well as maintenance expenses (related to total investment and maintenance frequency). Variable costs involve the expenditure on electricity for compressing hydrogen (dependent on hydrogen compression electricity usage and electricity rates) and are also influenced by the annual hydrogen throughput of the pipeline (connected to pipeline capacity and utilization rate).

The cost of pipeline hydrogen transportation is significantly influenced by the transportation distance and the utilization rate of pipeline capacity, which is positively correlated with the annual mass of hydrogen transmission.

To summarize, the unit cost of pipeline hydrogen transportation can be expressed by the following formula:

Unit cost of pipeline hydrogen transmission = Fixed Cost + Variable Cost = (Pipeline Depreciation + Maintenance Cost) + Electricity Cost of Compressed Hydrogen = [(Total Investment * Transportation Distance)/(Annual Hydrogen Transmission Mass * (1 - Hydrogen Transmission Loss Rate)]/Depreciation Life + (Electricity Consumption of Compressed Hydrogen * Electricity Price); Annual Hydrogen Transmission Mass = Annual Hydrogen Transmission Capacity * Capacity Utilization Rate

3) Liquid Hydrogen Tanker Truck Storage and Transportation

At present, the use of liquid hydrogen tanker truck storage and transportation in China is primarily limited to the military industry. This method is suitable for large-scale and long-distance transportation due to its higher efficiency in transporting hydrogen.

The unit cost of liquid hydrogen tanker truck storage and transportation comprises fixed and variable costs. Fixed costs include equipment depreciation (linked to liquid hydrogen tanker truck price and depreciation period), labor costs (related to per capita salary and the number of employees), and vehicle insurance. Variable costs include fuel (related to fuel consumption per 100 km and diesel fuel prices), vehicle maintenance costs, road tolls, and compressed hydrogen electricity (related to the electricity consumption of compressed hydrogen and the price of electricity). These costs are also influenced by the annual hydrogen transportation quantity of the tanker (related to single hydrogen transportation mass, number of round trips per day, and the number of working days per year).

In summary, the unit cost of hydrogen storage and transportation by liquid hydrogen tanker truck can be expressed by the following formula, where the value of the number of daily round trips by tanker truck is rounded down:

Unit cost of liquid hydrogen tanker truck storage and transportation = Fixed Cost + Variable Cost = (Depreciation of Equipment + Labor Cost + Vehicle Insurance) + (Fuel Cost + Vehicle Insurance Cost + Road Tolls + Electricity Cost of Compressed Hydrogen) = [Price of Liquid Hydrogen Tanker Truck/Depreciation Life (Salary Per Capita * No. of Employees) + Vehicle Insurance Cost (Fuel Consumption Per 100km * Price Of Diesel Fuel) + Vehicle Maintenance Cost + Road Tolls (Electricity Consumption of Compressed Hydrogen * Price Of Electricity)]/Mass of Hydrogen Shipped Per Annum; Annual Mass of Hydrogen Transportation = Liquid Hydrogen Tanker Truck Loading * Daily Round Trips * Annual Working Days = Liquid Hydrogen Tanker Truck Loading * Daily Working Hours/(Distance To Hydrogen Source/Average Speed Of Tanker * 2 + Hours of Refueling And Unloading of Hydrogen By Tanker) * Annual Operation Days

4.3.3 Hydrogen Refueling Cost Modeling Framework

At present, all hydrogen refueling stations in China operate using an external hydrogen supply mode. The cost per unit of hydrogen refueling primarily depends on several factors: the depreciation expenses associated with the construction and land costs of the refueling station, the duration over which these costs are depreciated, labor costs linked to employee salaries and numbers, and the operation and maintenance expenditures. Furthermore, this cost is influenced by the annual volume of hydrogen refueling at the station, which reflects its capacity utilization rate.

At present, the operational model of hydrogen refueling stations is still in the early stages of development, with significant potential for cost reduction in the future. This reduction will primarily focus on three key aspects: the price of hydrogen sources, the costs associated with storage and transportation, and the expenses related to refueling. Based on the discussion above, the reduction in hydrogen source prices is detailed in the "4.3.1 Hydrogen Production Cost Model," while the decrease in storage and transportation costs is explained in the "4.3.2 Hydrogen Transportation Cost Model." Regarding the reduction in hydrogen refueling costs, this primarily hinges on increasing the annual hydrogen refueling volume (thereby boosting the station's capacity utilization rate) and reducing depreciation expenses (achieved through optimizing construction costs).

In summary, the unit cost of refueling hydrogen and its strategies to cost reduction can be expressed using the formula (key factors affecting cost reduction are underlined):

Unit refueling cost of hydrogen = Depreciation Cost + Labor Cost + O&M Cost = [(Construction Cost/Depreciation Year of Construction Cost + Civil Construction Cost/Depreciation Year of Civil Construction Cost) (Salary Per Capita * No. Of Employees) +O&M Cost]/Annual Hydrogen Refueling Volume of Hydrogen Refueling Station; Annual Hydrogen Refueling Volume of Hydrogen Refueling Station = Daily Hydrogen Refueling Volume of

Hydrogen Refueling Station * Days of Annual Operation * Utilization Rate of Production Capacity

Unit refueling cost of hydrogen cost reduction = Depreciation Cost Reduction + Labor Cost + O&M Cost = [(Construction Cost Reduction/Depreciation Year of Construction Cost + Land Cost/Depreciation Year of Land Cost) + (Salary Per Capita * No. of Employees) + O&M Cost]/Growth of Annual Hydrogen Refueling Volume of Hydrogen Refueling Station; Growth of Annual Hydrogen Refueling Volume of Hydrogen Refueling Station = Daily Hydrogen Refueling Volume of Hydrogen Refueling Station * Days of Annual Operation * Growth of Production Capacity Utilization Rate

4.4 ESG Cost and Cost Reduction Modeling Framework

The Environmental Social Governance (ESG) cost plays a crucial role in determining the overall economy of vehicles. By assessing the carbon emissions across the entire lifecycle of various technology paths (such as conventional fuel, hydrogen, and pure electric), we can deduce the ESG cost as follows: ESG Cost = Whole Life Cycle Carbon Dioxide Emissions * Carbon Tax Price + Entire Life Cycle Carbon Dioxide Emissions * CCUS Whole Process Cost. This approach enables the creation of a more precise economic model.

CHAPTER 5: KEY ASSUMPTIONS AND DATA ANALYSIS

The preceding section provided an overview of the operating cost model framework for vehicles, along with the associated model framework for the industrial chain that impacts operating costs. This encompasses the cost model for the vehicle's core components as well as the cost model for the upstream hydrogen industrial chain. Building upon the foundation laid out in the previous chapter, this section will enumerate the key assumptions of each model in depth. Subsequently, it will undertake the calculation of these models, followed by a comprehensive analysis and discussion of the resultant data.

5.1 Operating Cost and Cost Reduction Model Analysis of Vehicles

Different application scenarios categorize vehicles into distinct types, including heavy-duty trucks, buses, logistics vehicles, and passenger vehicles. For improved readability, in this chapter, hydrogen fuel cell heavy-duty trucks are selected as an example. The operating costs of hydrogen fuel cell vehicles, conventional fuel vehicles, and pure electric vehicles under different technical routes will be measured and compared. Additionally, the future strategy of cost reduction for hydrogen fuel cell vehicles will be analyzed to assess the possibility of future widespread adoption of hydrogen fuel cell vehicles. This chapter exclusively provides the ultimate conclusions drawn from the model calculations for buses, logistics vehicles, and passenger vehicles. The detailed key assumptions underlying the models and the comprehensive process of data analysis are available in the Appendix.

1) Analysis of Operating Cost Model

1.1) Key Assumptions

The author employs a 49-ton hydrogen fuel cell heavy-duty truck equipped with a 125 kW-rated fuel cell system as a case study to compute the annual operating costs and outline cost-reduction trajectories. These findings are juxtaposed with those of a conventional fuel-powered heavy-duty truck and a fully electric heavy-duty truck. To comprehensively compare the economics of each technology route, this model currently excludes the subsidy factor. However, it will be addressed later as a policy regulation tool to steer cost-reduction efforts. The key assumptions of the model for the current time node are outlined below:

1）<u>Purchase cost</u>: Without factoring in subsidies, the price of a hydrogen fuel cell heavy-duty truck is 1.35 million yuan, while a conventional fuel heavy-duty truck costs 400,000 yuan, and a purely electric heavy-duty truck is priced at 900,000 yuan.

2）<u>Vehicle depreciation</u>: The vehicles are depreciated over a 5-year operational lifespan, assuming a 5% residual value at the end of that period.

3）<u>Fuel cost</u>:

- <u>Energy consumption per 100 km</u>: For hydrogen fuel cell heavy-duty trucks, the hydrogen consumption per 100 km is 8.8 kg. In comparison, conventional fuel heavy-duty trucks consume 35 L of fuel per 100 km, while purely electric heavy-duty trucks require 240 kWh of electricity per 100 km.

- Energy price: The cost of hydrogen is 35 yuan per kg, conventional fuel costs 8 yuan per liter, and electricity is priced at 0.67 yuan per kWh.
- Driving range: 400 km per day, 365 days of operation per year.

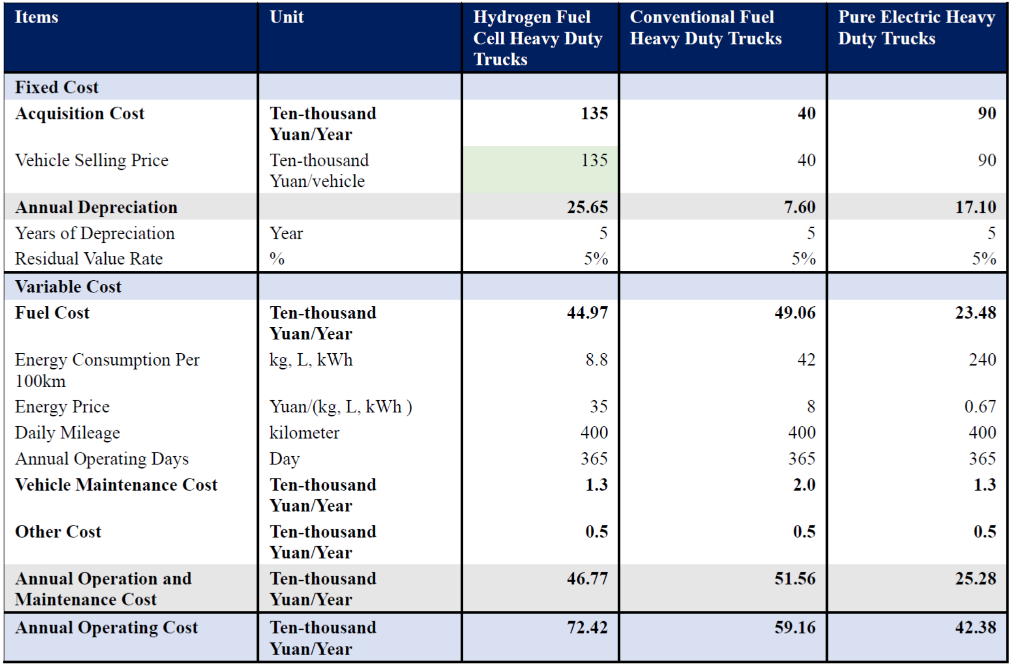
4）Vehicle maintenance fee: The annual cost for hydrogen fuel cell heavy-duty trucks and purely electric heavy-duty trucks is 13,000 yuan each, while for conventional fuel heavy-duty trucks, it is 20,000 yuan.

5）Other costs: 50,000 yuan/year for all. Furthermore, the purchase contract includes a 5-year full life-cycle warranty, with no additional cost for maintenance.

1.2) Data Analysis

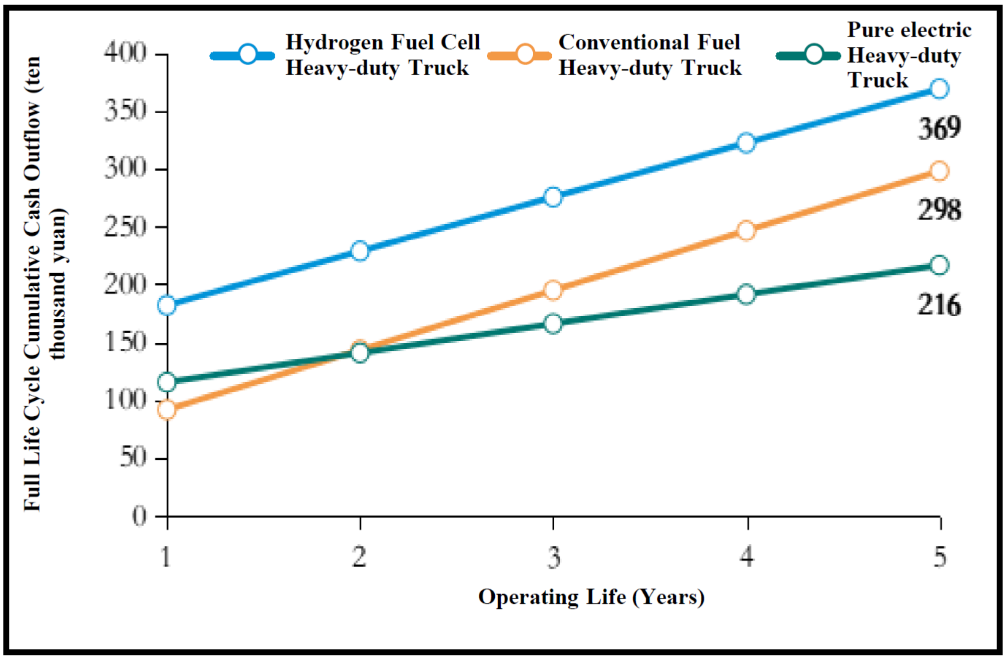
According to the model calculations, without factoring in subsidies, the current operating cost of hydrogen fuel cell heavy-duty trucks amounts to 724,200 yuan per year. This figure is notably higher compared to conventional fuel heavy-duty trucks, which stand at 591,600 yuan per year, and pure electric heavy-duty trucks, which total 423,800 yuan per year. The primary reason for this disparity is that unsubsidized hydrogen fuel cell vehicles are sold at a considerably higher price than their conventional fuel and pure electric counterparts. Additionally, while the operation and maintenance costs of hydrogen fuel cell heavy-duty trucks are lower than those of conventional fuel heavy-duty trucks, they are higher than those of pure-electric heavy-duty trucks. In contrast, despite the higher initial acquisition cost of pure electric heavy-duty trucks, their lower operation and maintenance costs result in a reduced cumulative cash flow expenditure by the second year of operation compared to conventional fuel heavy-duty trucks. Subsequently, economic advantages continue to expand year by year. This inherent momentum serves as a driving force to promote substitution. Therefore, the core factor enabling the application of hydrogen fuel cell heavy-duty trucks is the reduction of acquisition costs (assuming constant profit margins, tied to manufacturing costs) and fuel costs (linked to hydrogen consumption per 100 km and hydrogen price) through technological progress and industrial scaling. (Refer to "Fig. 5.1.1.1 Comparison of Operating Costs of Heavy-duty trucks under Different Technology Routes" and "Fig. 5.1.1.2 Comparison of Full Life Cycle Cumulative Cash Outflows of Heavy-duty trucks under Different Technology Routes" for more details).

Fig. 5.1.1.1 Comparison of Operating Costs of Heavy-duty Trucks under Different Technology Routes



Items	Unit	Hydrogen Fuel Cell Heavy Duty Trucks	Conventional Fuel Heavy Duty Trucks	Pure Electric Heavy Duty Trucks
Fixed Cost				
Acquisition Cost	**Ten-thousand Yuan/Year**	**135**	**40**	**90**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	135	40	90
Annual Depreciation		**25.65**	**7.60**	**17.10**
Years of Depreciation	Year	5	5	5
Residual Value Rate	%	5%	5%	5%
Variable Cost				
Fuel Cost	**Ten-thousand Yuan/Year**	**44.97**	**49.06**	**23.48**
Energy Consumption Per 100km	kg, L, kWh	8.8	42	240
Energy Price	Yuan/(kg, L, kWh)	35	8	0.67
Daily Mileage	kilometer	400	400	400
Annual Operating Days	Day	365	365	365
Vehicle Maintenance Cost	**Ten-thousand Yuan/Year**	**1.3**	**2.0**	**1.3**
Other Cost	**Ten-thousand Yuan/Year**	**0.5**	**0.5**	**0.5**
Annual Operation and Maintenance Cost	**Ten-thousand Yuan/Year**	**46.77**	**51.56**	**25.28**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**72.42**	**59.16**	**42.38**

Fig. 5.1.1.2 Comparison of Full Life Cycle Cumulative Cash Outflows of Heavy-duty Trucks under Different Technology Routes



2) Analysis of Operating Cost Reduction Model

2.1) Key Assumptions

The manufacturing cost of hydrogen fuel cell heavy-duty trucks is primarily determined by upstream components. Among these, the fuel cell system (53% of the cost), hydrogen storage system (17%), and battery system (10%) are the core components of hydrogen fuel cell heavy-duty trucks. They are still in the early stages of industrial research and development, leaving ample room for future cost reductions. The powertrain system (7%) and body and other facilities (13%) are more mature components that have already been applied in conventional fuel heavy-duty trucks. This information is illustrated in Fig. 5.1.1.3, depicting the cost structure of a 49-ton hydrogen fuel cell heavy-duty truck. The operation and maintenance cost is primarily influenced by the fuel cost, which is directly tied to the hydrogen consumption per 100 km and the price of hydrogen refueling (see 5.3 Hydrogen Industry Supply Chain Cost and Cost Reduction Model).

Therefore, the key assumptions of the cost-reduction model for hydrogen fuel cell heavy-duty trucks are as follows (refer to "Fig. 5.1.1.4 Annualized Cost Reduction Assumptions for Hydrogen Fuel Cell Vehicles and the Hydrogen Industry Supply Chain", which are also applicable to other vehicle scenarios powered by hydrogen, such as buses, logistic vehicles, and passenger vehicles):

1) Profit Margin: Assuming a constant gross profit margin of 20%, the manufacturing cost of a hydrogen fuel cell heavy-duty truck accounts for 80% of the vehicle's selling price.

2) Manufacturing Cost:

- Fuel Cell System Cost: Since the components are not yet in large-scale production, while domestic technology is essentially prepared, the author speculates that there will be rapid and sustained cost reduction. The current cost of the fuel cell system is 5,000 yuan per kilowatt (kW), and according to the forecast of the Energy Saving and New Energy Vehicle Technology Roadmap, the cost of the fuel cell system is expected to decrease to 2,000 yuan/kW by 2025 and further decrease to 600 yuan/kW by 2050. The model presumes a yearly decrease of about 25% between 2022 and 2025, followed by a reduction of around 20% from 2025 to 2030.
- Hydrogen Storage System Cost: The majority of cost components stem from raw materials, particularly the core materials used in hydrogen storage, such as carbon fiber, which still require overseas procurement. Consequently, the author suggests a more conservative estimate for cost

reduction. Based on the projections from the "China Hydrogen Energy Industry Development Report 2020", the cost of hydrogen storage systems is anticipated to be 5,000 yuan/kg in 2020, decreasing to 3,500 yuan/kg by 2025, and further dropping to 2,000 yuan/kg by 2035. The model assumes an average annual reduction of 7% in energy storage system costs from 2020 to 2025, followed by a 5% reduction from 2025 to 2030.

- Battery System: Given the increased maturity of the technology, along with its application in both conventional fuel vehicles and pure electric vehicles, the author suggests a more conservative estimate for cost reduction. Taking into account the dual factors of power battery technology iteration leading to cost reduction and the concurrent decrease in material costs, this model assumes an average annual reduction in power battery prices of 5% from 2022 to 2030.

3）Operation and Maintenance Costs:

- Hydrogen Consumption per 100 Km: The advancement in technology promotes fuel efficiency, resulting in a decline in hydrogen consumption per 100 km. As per this model, it is assumed that hydrogen consumption per 100 km decreases at an average annual rate of 3%.
- Hydrogen Refueling Price: Due to the hydrogen industry supply chain, encompassing "preparation, storage, transportation, and refueling", the hydrogen production segment has steadily matured, with gas prices remaining stable. A 5-10% cost reduction primarily stems from technological advancements in efficiency, such as electrolysis of water to produce hydrogen. Conversely, the storage, transportation, and refueling segments are directly correlated with capacity utilization. Therefore, with

the gradual expansion of industry scale, the author predicts a 10-20% cost reduction in these areas. Presently, the subsidized terminal hydrogen price stands at yuan 35 yuan/kg. Anticipating technological iteration and the extensive operation of the hydrogen industry supply chain encompassing "preparation, storage, transportation, and refueling", the terminal hydrogen price is predicted to decrease to 30 yuan/kg by 2025 and 20 yuan/kg by 2030. For a detailed explanation of the specific cost-reduction model, please refer to section 5.3 Hydrogen Industry Supply Chain Cost and Cost Reduction Model.

Fig. 5.1.1.3 Cost Structure of a 49-ton Hydrogen Fuel Cell Heavy-duty Truck

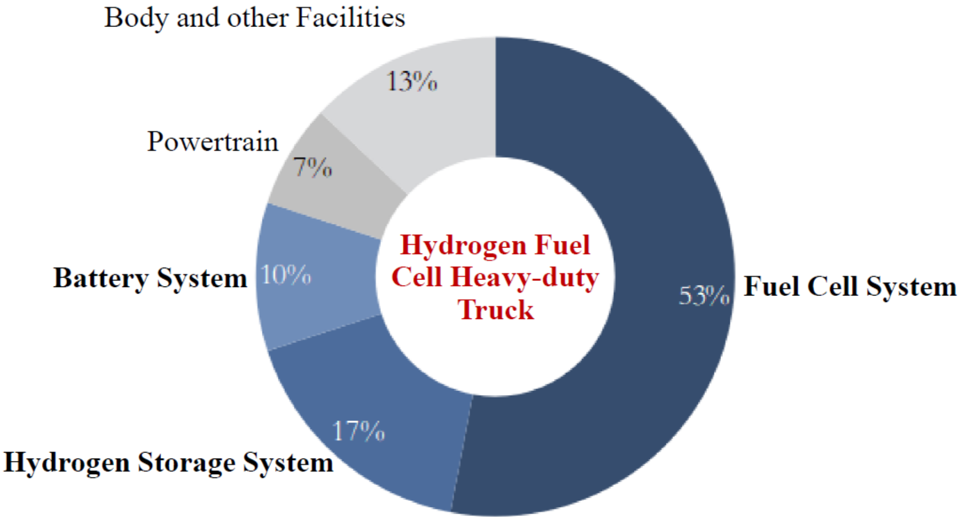


Fig. 5.1.1.4 Annualized Cost Reduction Assumptions of Hydrogen Fuel Cell Vehicles and Hydrogen Industry Supply Chain

Annualized Cost Reduction Assumptions		Unit	2022-2025	2026-2030	Remarks
Hydrogen Fuel Cell Vehicle Components	Fuel Cell System	%	25%	20%	Although the components are not yet being produced on a large scale, domestic technology is essentially prepared. Therefore, the authors speculate that there will be rapid and sustained cost reductions.
	Hydrogen Storage System	%	7%	5%	The majority of the costs are attributed to raw materials, particularly the core materials for hydrogen storage like carbon fiber, which still need to be sourced from overseas. Therefore, the authors anticipate a slower rate of cost reduction.
	Battery System	%	5%	5%	The technology is more mature and has already been applied in conventional fuel vehicles and pure electric vehicles. Therefore, the authors anticipate a slower rate of cost reduction.
Hydrogen Industry Supply Chain	Preparation	%	10%	5%	Hydrogen production has become increasingly mature, and gas prices have remained stable. The projected cost reduction of 5 to 10% is primarily attributed to efficiency improvements resulting from technological advancements, such as enhanced electrolysis of water for hydrogen production.
	Storage and Transportation	%	10%	10%	Storage, transportation, and refueling costs are directly tied to capacity utilization rates. As the industry scale gradually expands, the authors anticipate a cost reduction range of 10-20%.
	Refueling	%	20%	10%	
Hydrogen Efficiency	100km Hydrogen Consumption	%	3%	3%	Technology iteration is driving improvements in fuel efficiency, resulting in a decline in hydrogen consumption per 100 kilometers.

2.2) Data Analysis

Setting aside the cost-reduction paths of conventional fuel heavy-duty trucks and pure electric heavy-duty trucks for the time being, the operating cost of hydrogen fuel cell heavy-duty trucks in 2030 is projected to be 333,600 yuan per year. This figure is lower than the current operating costs of conventional fuel heavy-duty trucks, which stand at 591,600 yuan per year, as well as pure electric heavy-duty trucks, which amount to 423,800 yuan per year. The primary reason is that the projected selling price of hydrogen fuel cell heavy-duty trucks in 2030 is 600,000 yuan, which is higher than that of current conventional fuel heavy-duty trucks (400,000 yuan) but lower than that of pure electric heavy-duty trucks (900,000 yuan). In 2030, the operations and maintenance (O&M) cost of hydrogen fuel cell heavy-duty trucks is projected at only 219,400 yuan per year, which is less than the current O&M cost of conventional fuel heavy-duty trucks (515,600 yuan per year) and pure electric heavy-duty trucks (252,800 yuan per year). In summary, when considering overall cost efficiency, hydrogen fuel cell heavy-duty trucks are expected to be the most competitive alternative to pure electric heavy-duty trucks within the commercial vehicle sector. Current policy subsidies are primarily directed towards guiding the adoption of these hydrogen fuel cell models. With advancements in hydrogen fuel cell technology in terms of system power, these trucks are anticipated to lead the way in development, as illustrated in "Fig. 5.1.1.5 & Fig. 5.1.1.6 Hydrogen fuel cell Heavy-duty Truck Operating Cost Reduction Calculation" and 6.1 Jinnan Iron and Steel Case.

Fig. 5.1.1.5 Hydrogen Fuel Cell Heavy-duty Truck Operating Cost Reduction Calculation

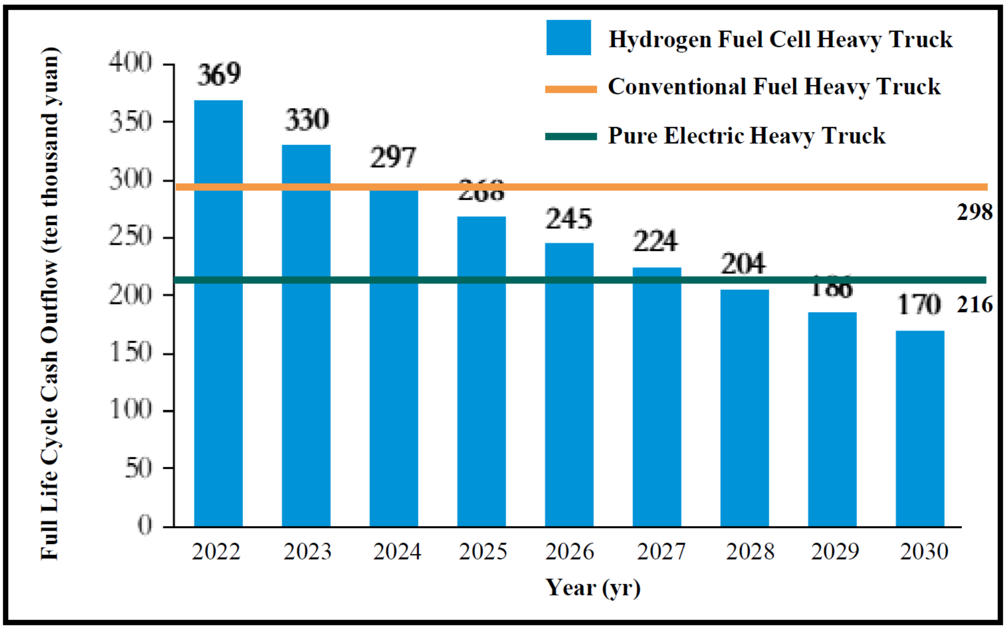


Fig. 5.1.1.6 Hydrogen Fuel Cell Heavy-duty Truck Operating Cost Reduction Calculation

Items	Unit	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fixed Cost										
Manufacturing Cost	**Ten-thousand yuan**	**108**	**92**	**79**	**70**	**64**	**59**	**55**	**51**	**48**
Fuel Cell System	Ten thousand yuan	57	43	32	24	19	15	12	10	8
Average Annual Reduction	*%*		*25%*	*25%*	*25%*	*20%*	*20%*	*20%*	*20%*	*20%*
Hydrogen Storage System	Ten thousand yuan	18	17	16	15	14	13	13	12	11
Average Annual Reduction	*%*		*7%*	*7%*	*7%*	*5%*	*5%*	*5%*	*5%*	*5%*
Battery System	Ten thousand yuan	11	10	10	9	9	8	8	8	7
Average Annual Reduction	*%*		*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
Acquisition Cost	**Ten thousand yuan**	**135**	**115**	**99**	**87**	**80**	**73**	**68**	**64**	**60**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	135	115	99	87	80	73	68	64	60
Subsidy	Ten-thousand Yuan/vehicle	-	-	-	-	-	-	-	-	-
Subsidy Factor	-	-	-	-	-	-	-	-	-	-
Annual Depreciation	**Ten-thousand Yuan/Year**	**25.7**	**21.8**	**18.9**	**16.6**	**15.1**	**14.0**	**13.0**	**12.1**	**11.4**
Years of Depreciation	Year	5	5	5	5	5	5	5	5	5
Residual Value Rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Variable Cost										
Fuel Cost	**Ten-thousand Yuan/Year**	**45**	**41**	**38**	**34**	**31**	**28**	**25**	**23**	**20**
100km Hydrogen Consumption	kg/100km	8.8	8.5	8.3	8.0	7.8	7.6	7.3	7.1	6.9
Average Annual Reduction	*%*		*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*
Retail Price of Hydrogen	Yuan/kg	35	33	31	29	28	26	24	22	20
Daily Mileage	kilometer	400	400	400	400	400	400	400	400	400
Annual Operating Days	Day	365	365	365	365	365	365	365	365	365
Vehicle Maintenance Cost	**Ten-thousand Yuan/Year**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
Other costs	**Ten-thousand Yuan/Year**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Annual Operation and Maintenance Cost	**Ten-thousand Yuan/Year**	**47**	**43**	**40**	**36**	**33**	**30**	**27**	**25**	**22**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**72**	**65**	**58**	**53**	**48**	**44**	**40**	**37**	**33**

Likewise, in other application scenarios such as buses, logistics vehicles, and passenger vehicles, the author applied the same concepts to develop operating cost and cost-reduction models for these vehicles. To enhance the readability of the thesis and minimize repetition, only the final conclusions from the model calculations under various scenarios are presented here. The detailed content of the key assumptions and data analysis is provided in the appendix.

Excluding the cost-reduction strategies applied to conventional fuel logistics vehicles and pure electric logistics vehicles, the operating cost of hydrogen fuel cell buses in 2030 is projected to be 229,100 yuan per year. This cost remains higher compared to the current operating costs of conventional fuel buses (199,600 yuan/year) and pure electric buses (153,800 yuan/year). The primary reason for the higher operating cost of hydrogen fuel cell buses in 2030 is attributed to their vehicle selling price, which is projected to be 1.04 million yuan. This selling price significantly exceeds that of current conventional fuel buses (500,000 yuan) and pure electric buses (800,000 yuan). However, the operations and maintenance (O&M) cost of hydrogen fuel cell buses in 2030 is estimated to be 106,000 yuan/year, which is lower than the current O&M cost of conventional fuel buses (140,200 yuan/year), but significantly higher than the O&M cost of pure electric buses (58,800 yuan/ year). In summary, based solely on the final economic analysis, hydrogen fuel cell buses lack the inherent competitiveness to rival pure electric buses (refer to "Fig. 5.1.2.1 Hydrogen fuel cell Bus Operating Cost Reduction Calculation").

Excluding the cost-reduction strategies applied to conventional fuel logistics vehicles and pure electric logistics vehicles, the operating cost of hydrogen fuel cell logistics vehicles in 2030 is projected to be 102,500 yuan/year. This cost is lower than the current operating cost of conventional fuel logistics vehicles (120,800 yuan/year), but higher than the operating cost of pure electric logistics vehicles (87,600 yuan/year). The main reason for the higher operating cost of hydrogen fuel cell logistics vehicles in 2030 is attributed to their vehicle selling price, which is projected to be 490,000 yuan. This selling price is still higher compared to the current selling prices of conventional fuel logistics vehicles (200,000 yuan) and pure electric logistics vehicles (400,000 yuan). However, the operations and maintenance (O&M) cost of hydrogen fuel cell logistics vehicles in 2030 is estimated to be only 44,800 yuan per year, which is significantly lower than the current O&M cost of conventional fuel logistics vehicles (97,000 yuan/year) and comparable to that of pure electric logistics vehicles (40,100 yuan/year). In summary, based solely on the final economic analysis, hydrogen fuel cell logistics vehicles are expected to have the inherent competitiveness to compete with pure electric logistics vehicles, particularly in scenarios with high energy consumption such as cold chain vehicles (refer to 6.2 GLP's Case for details). However, further reductions in manufacturing costs are necessary to fully leverage the economic advantages of hydrogen fuel cell logistics vehicles (refer to "Fig. 5.1.3.1 Hydrogen Fuel Cell Logistics Vehicle Operating Cost Reduction Calculation").

Fig. 5.1.2.1 Hydrogen Fuel Cell Bus Operating Cost Reduction Calculation

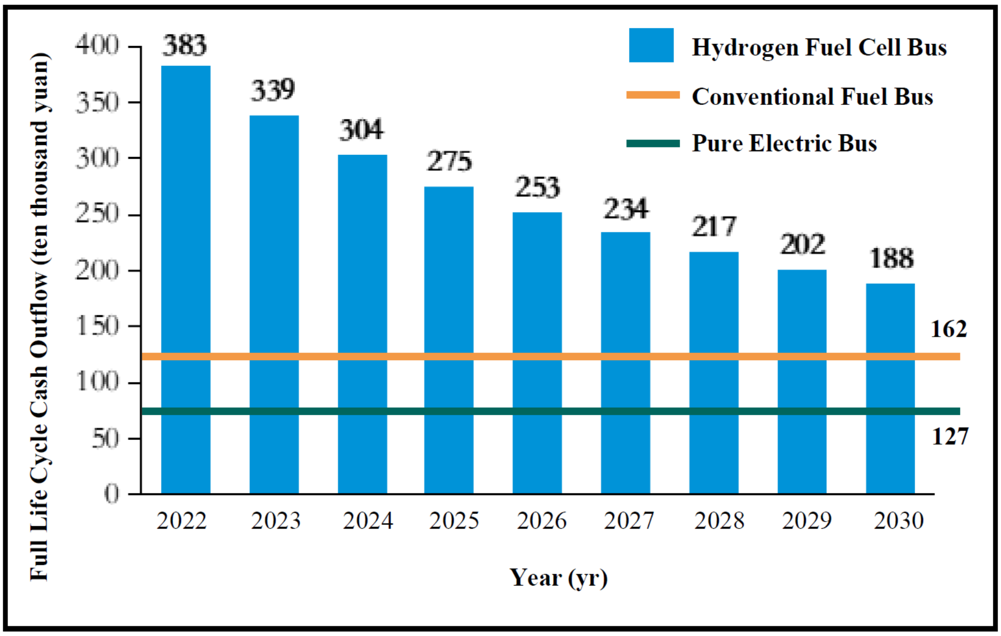
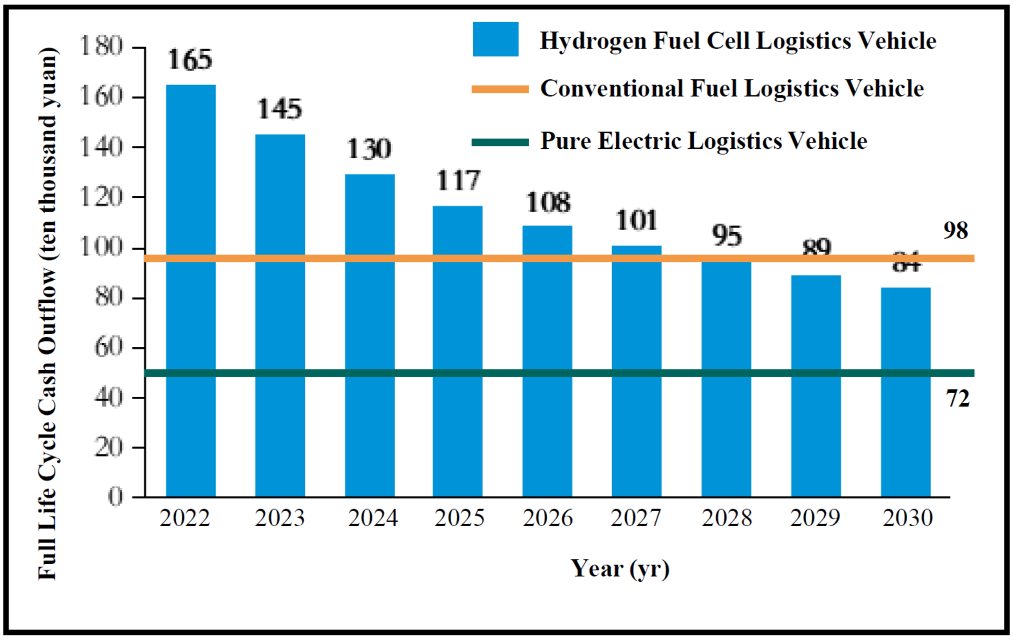
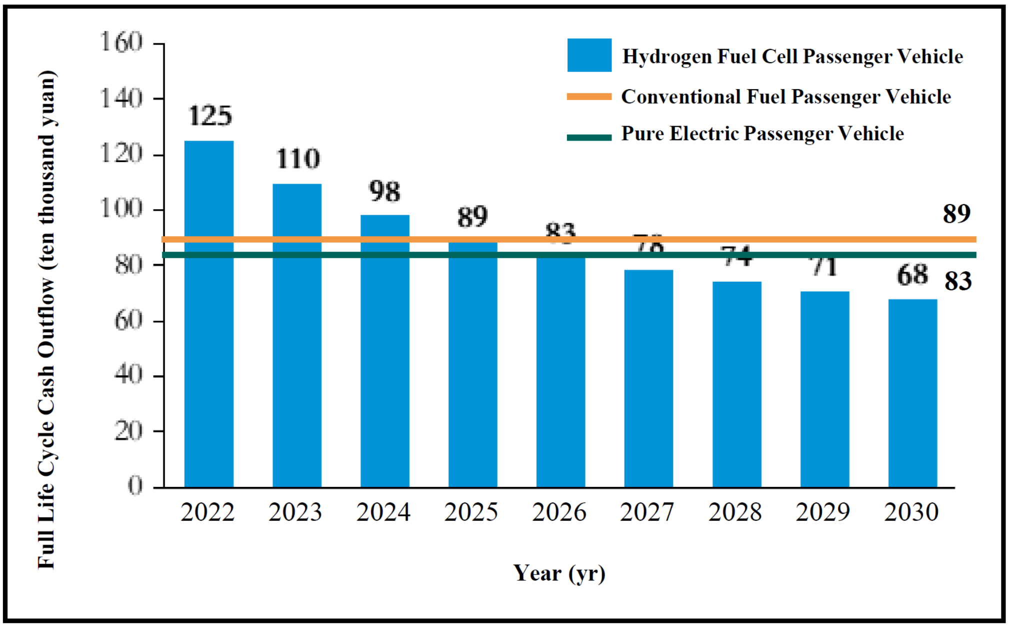


Fig. 5.1.3.1 Hydrogen Fuel Cell Logistics Vehicle Operating Cost Reduction Calculation



Excluding the cost-reduction strategies applied to conventional fuel passenger vehicles and pure electric passenger vehicles, the operating cost of hydrogen fuel cell passenger vehicles in 2030 is projected to be 81,900 yuan per year. This cost is lower than the current operating cost of conventional fuel passenger vehicles (107,600 yuan/year) and pure electric passenger vehicles (99,400 yuan/year). The main reason for the lower operating cost of hydrogen fuel cell passenger vehicles in 2030 is attributed to their vehicle selling price, which is projected to be 490,000 yuan. This selling price is lower compared to the current selling prices of conventional fuel passenger vehicles (620,000 yuan) and pure electric logistics vehicles (650,000 yuan). The operations and maintenance (O&M) cost of hydrogen fuel cell passenger vehicles in 2030 is estimated to be only 23,400 yuan/year, which is lower than the current O&M cost of conventional fuel passenger vehicles (34,000 yuan/year) and roughly equivalent to that of pure electric passenger vehicles (22,200 yuan/year). In summary, based solely on the final economic analysis, hydrogen fuel cell passenger vehicles are expected to possess the inherent competitiveness to compete with pure electric passenger vehicles. However, further reductions in manufacturing costs are needed to fully unlock the economic advantages (refer to "Fig. 5.1.4.1 Hydrogen fuel cell Passenger Vehicle Operating Cost Reduction Calculation"). The consideration of infrastructure also supports the model's conclusion in this thesis that heavy-duty trucks represent the optimal scenario for hydrogen fuel cell vehicles, particularly due to their fixed routes.

Fig. 5.1.4.1 Hydrogen Fuel Cell Passenger Vehicle Operating Cost Reduction Calculations



Based on the modeling described above, it will require a minimum of 3 years for the entire life cycle cash flow of hydrogen fuel cell passenger vehicles to match that of pure electric passenger vehicles. Referring to data from the China Association of Passenger Vehicle Manufacturers (CAPVM), the current adoption rate of electric passenger vehicles (including pure electric and hybrid) in China has surpassed 40%, with expectations for continued growth in the future. The author asserts that electric passenger vehicles enjoy a distinct first-mover advantage, leveraging initial national and local resource subsidies along with established infrastructure advantages such as charging stations and power-exchange facilities. Although hydrogen fuel cell passenger vehicles theoretically offer advantages in end-game economics, their late entry into the market, combined with the decentralized nature of passenger vehicle usage and the need for flexible hydrogen refueling, present challenges. The development and implementation of actual infrastructure, such as hydrogen refueling stations and hydrogen storage and transportation systems, are slower and require substantial upfront investments. The potential for large-scale commercialization of hydrogen fuel cell passenger vehicles remains highly uncertain until infrastructure challenges are effectively addressed.[29, 30]

In conclusion, for various vehicle application scenarios, hydrogen fuel cell heavy-duty trucks demonstrate economic advantages over vehicles utilizing other technology routes (conventional fuel and pure electric). This is achieved by implementing reasonable cost-reduction assumptions for core components of hydrogen fuel cell vehicles and the hydrogen industry supply chain. Firstly, the selling price of hydrogen fuel cell heavy-duty trucks can be lowered to a competitive level. Secondly, the operation and maintenance costs of hydrogen fuel cell heavy-duty trucks are significantly lower compared to vehicles using other technologies (conventional fuel and pure electric). Given that heavy-duty trucks often operate on fixed driving routes, hydrogen fuel cell heavy-duty trucks represent the optimal vehicle application scenario, particularly considering the infrastructure requirements of hydrogen fuel cell vehicles. Similarly, hydrogen fuel cell logistics vehicles operating in specialized areas such as cold chain transportation demonstrate certain economic advantages over vehicles using other technology routes (conventional fuel and pure electric). Besides the potential reduction in vehicle price to a competitive range, the primary reason for this advantage is that hydrogen fuel cell logistics vehicles outperform pure electric logistics vehicles in terms of operation and maintenance costs, especially in high-energy-consumption scenarios like cold chain transportation. For hydrogen fuel cell buses, there are two primary challenges despite cost reduction efforts: Firstly, the selling price of the vehicles remains high even after reduction; Secondly, the operation and maintenance costs, even after reduction, are still twice as much as those of pure electric buses, which negates any significant economic advantages. For hydrogen fuel cell passenger vehicles, while efforts to reduce vehicle selling prices and operation and maintenance costs are advantageous, the flexible operational nature of passenger vehicles necessitates substantial infrastructure investments, including hydrogen refueling stations and hydrogen storage and transportation systems. In comparison, the existing charging stations and power-exchanging facilities for pure electric passenger vehicles already provides a clear first-mover advantage.

5.2 Cost and Cost Reduction Model Analysis of Core Parts

The cost of core components in hydrogen fuel cell vehicles is a crucial factor influencing their manufacturing cost. Key components such as the fuel cell system, hydrogen storage system, and battery system constitute a significant portion of the total cost. Based on the current prices of core components such as the fuel cell system, hydrogen storage system, and battery system, the author applies reasonable average annual reduction rates (projected until 2030) to predict the manufacturing cost of hydrogen fuel cell vehicles and outline the path of cost reduction. Specifically, the author estimates annual reduction rates of 20-25% for the fuel cell system, 5-7% for the hydrogen storage system, and 5% for the battery system. These projections are used to assess the feasibility of launching hydrogen fuel cell vehicles (refer to "Fig. 5.1.1.4 Annualized Cost Reduction Assumptions for Hydrogen fuel cell Vehicles and Hydrogen Industry Supply Chain" for more details).

Furthermore, the author predicts the declining trajectory of the selling price of hydrogen fuel cell vehicles based on the learning curve associated with the cost and scale of the new-energy industry. The outcomes derived from both of these measurement methods are expected to align closely with each other.

5.3 Cost and Cost Reduction Model Analysis of Hydrogen Industry Supply Chain

The hydrogen energy upstream industry is segmented into three key stages: hydrogen production, storage and transportation, and refueling. The hydrogen price is the central element that determines whether hydrogen fuel cell vehicles can achieve cost competitiveness. The U.S. Department of Energy (DOE) has set cost reduction targets for each stage of the hydrogen supply chain, aiming to bring the cost of preparation down to \$1/kg and the cost of storage and transportation down to \$3/kg.

The author contends that the primary drivers for future cost reduction in each segment of the hydrogen energy industry include scaling up production, enhancing equipment technology and processes, and reducing energy prices. The author has conducted measurements and comparisons of costs associated with various technical strategies across different segments of the hydrogen energy industry, including preparation, storage, transportation, and refueling. Through this analysis, the author assesses future cost-reduction trajectories and uses these insights to evaluate the feasibility of scaling up hydrogen fuel cell vehicles. [31-34]

Additionally, the author predicts the cost-reduction trajectory of hydrogen price based on the learning curve of cost and scale in the new-energy industry. The outcomes derived from these two measurement methods are expected to be comparable and aligned.

5.3.1 Hydrogen Preparation

The primary methods for preparing hydrogen include: 1) producing hydrogen from conventional fuels (such as coal or natural gas); 2) generating hydrogen through water electrolysis (utilizing alkaline, PEM, or SOEC methods); and 3) obtaining hydrogen as a by-product of industrial processes.

Given that the cost structure of industrial by-production of hydrogen varies depending on different raw materials, and considering that solid oxide electrolysis (SOEC) technology is not yet commercially viable, this thesis specifically focuses on four hydrogen production methods: hydrogen from coal, natural gas, alkaline electrolysis, and proton exchange membrane (PEM) electrolysis. These methods are used to construct a theoretical cost model for discussion within the thesis.

1) Cost Model of Hydrogen Production from Coal

1.1) Key Assumptions

Coal-based hydrogen production technology is mature and low-cost, but it is associated with high carbon emissions. The key factor influencing the cost of coal-based hydrogen production is the price of coal. The author uses a 90,000 m^3/h hydrogen production plant scale as an example and analyzes the cost of hydrogen production by varying the price of coal. To comprehensively assess the economics of hydrogen production, this model currently excludes subsidy factors. However, it will serve as a reference for discussing policy and regulatory measures aimed at cost reduction in the future. The key assumptions of the model at the current time node are as follows:

1) Hydrogen Production Scale: The scale of the hydrogen production plant is 90,000 m^3/hour, and the annual working time is 8,000 hours.

2) Hydrogen Density: 0.0893 kg/m^3 in a standard case.

3) Fixed Cost:

- Depreciation Cost: The construction cost amounts to 1.24 billion yuan, with a salvage rate of 5%. Additionally, there is an annual repair cost equivalent to 3% of the construction cost. All these expenses are depreciated over a 20-year period of operation.
- Labor Cost: Per capita salary of 80,000 yuan/person-year, with a staff of 108.
- Finance Cost: The loan amount is set at 70% of the construction cost, accruing an annual interest rate of 5%.

4) Variable Cost:

- Coal Cost: Producing 1 m^3 of hydrogen requires approximately 0.76 kg of coal. The price of coal ranges from 200 to 1,000 yuan per ton.
- Other Material Cost: Producing 1 m^3 of hydrogen gas requires approximately 0.42 m^3 of oxygen, along with 0.043 yuan worth of auxiliary materials. The price of oxygen is 0.5 yuan/m^3.
- Fuel Power Cost: Producing 1 m^3 of hydrogen requires approximately 0.043 kWh of electricity, 8 kg of circulating water, 0.25 kg of fresh water, and 3.6 kg of desalinated water. The prices for these resources are as

follows: electricity costs 0.56 yuan per kWh, circulating water costs 1 yuan/m^3, fresh water costs 4 yuan/m^3, and desalinated water costs 10 yuan/m^3.

- Carbon Capture Cost: Producing 1 kg of hydrogen results in 22 kg of carbon emissions. The cost of capturing 1 kg of CO_2 is 0.175 yuan.

1.2) Data Analysis

According to the model, the cost of coal-based hydrogen production is directly correlated with the price of coal. In the absence of subsidies and without carbon capture, when the coal price is 450 yuan/ton, the cost of hydrogen production is 9.74 yuan/kg, which accounts for 39% of the total cost of coal-based hydrogen production. Due to the significant carbon emissions associated with coal-based hydrogen production, the cost of hydrogen production after considering carbon capture increases to 13.59 yuan/kg. When the coal price rises to 1,000 yuan/ton, the cost of hydrogen production without carbon capture increases to 14.42 yuan/kg, while the cost of hydrogen production after considering carbon capture rises to 18.27 yuan/kg. In this scenario, the hydrogen product, after implementing carbon capture, transitions from grey hydrogen to blue hydrogen (refer to "Fig. 5.3.1.1 & Fig. 5.3.1.2 Sensitivity Calculation of Coal-to-Hydrogen Cost to Coal Price").

Fig. 5.3.1.1 Sensitivity Calculation of Coal-to-Hydrogen Cost to Coal Price

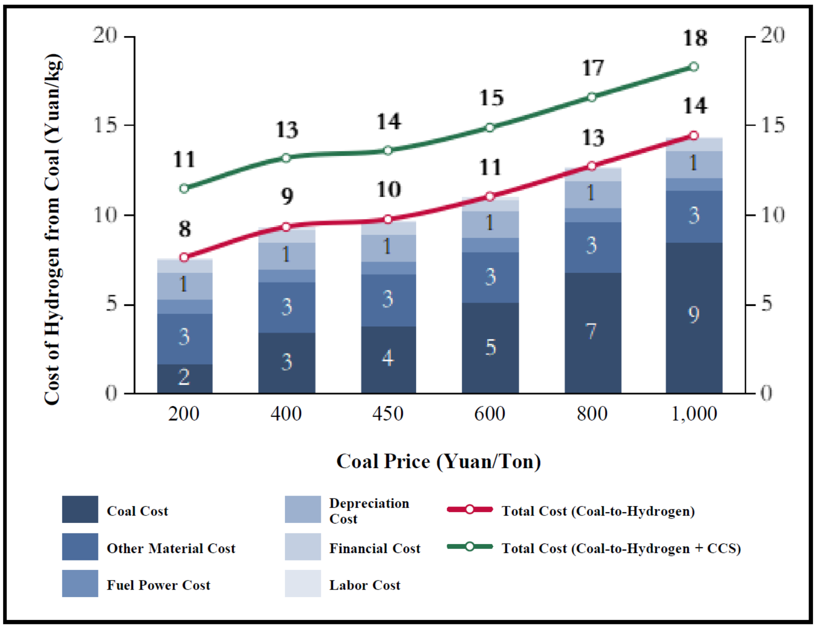


Fig. 5.3.1.2 Sensitivity Calculation of Coal-to-Hydrogen Cost to Coal Price

Coal Price	Unit	200	400	450	600	800	1,000
Annual Hydrogen Production Scale	**10,000 m^3**	**72,000**	**72,000**	**72,000**	**72,000**	**72,000**	**72,000**
Scale of Hydrogen Production Plant	m^3/h	90,000	90,000	90,000	90,000	90,000	90,000
Annual Working Time	h	8,000	8,000	8,000	8,000	8,000	8,000
Hydrogen Density	**kg/m^3**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**
Fixed Cost	**Yuan/kg**	**2.30**	**2.30**	**2.30**	**2.30**	**2.30**	**2.30**
Depreciation Cost	**Yuan/kg**	**1.49**	**1.49**	**1.49**	**1.49**	**1.49**	**1.49**
Construction Cost	Ten thousand yuan	124,000	124,000	124,000	124,000	124,000	124,000
Years of Depreciation	Year	20	20	20	20	20	20
Annual Maintenance Cost	%	3%	3%	3%	3%	3%	3%
Residual Value Rate	%	5%	5%	5%	5%	5%	5%
Labor Cost	**Yuan/kg**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**
Per Capita Salary	Ten-thousand Yuan /Person-Year	8.00	8.00	8.00	8.00	8.00	8.00
Number of employees	People	108	108	108	108	108	108
Finance Cost	**Yuan/kg**	**0.68**	**0.68**	**0.68**	**0.68**	**0.68**	**0.68**
Loan Amount	%	70%	70%	70%	70%	70%	70%
Annual Interest Rate	%	5%	5%	5%	5%	5%	5%
Variable Cost	**Yuan/kg**	**5.31**	**7.01**	**7.44**	**8.71**	**10.42**	**12.12**
Coal Cost	**Yuan/kg**	**1.70**	**3.40**	**3.83**	**5.11**	**6.81**	**8.51**
Coal Consumption	kg/m^3 H_2	0.76	0.76	0.76	0.76	0.76	0.76
Other Material Cost	**Yuan/kg**	**2.83**	**2.83**	**2.83**	**2.83**	**2.83**	**2.83**
Oxygen Cost	**Yuan/kg**	**2.35**	**2.35**	**2.35**	**2.35**	**2.35**	**2.35**
Oxygen Consumption	$m3/m^3$ H_2	0.42	0.42	0.42	0.42	0.42	0.42
Oxygen Price	Yuan/m^3	0.50	0.50	0.50	0.50	0.50	0.50
Auxiliary Material Cost	**Yuan/kg**	**0.48**	**0.48**	**0.48**	**0.48**	**0.48**	**0.48**
Auxiliary Material Price	Yuan/m^3 H_2	0.043	0.043	0.043	0.043	0.043	0.043
Fuel Power Cost	**Yuan/kg**	**0.77**	**0.77**	**0.77**	**0.77**	**0.77**	**0.77**
Electricity Cost	**Yuan/kg**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**	**0.27**
Electricity Consumption	kWh/m^3 H_2	0.043	0.043	0.043	0.043	0.043	0.043
Electricity Price	Yuan/kWh	0.56	0.56	0.56	0.56	0.56	0.56
Circulating Water Cost	**Yuan/kg**	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**	**0.09**
Circulating Water Consumption	kg/m^3 H_2	8.00	8.00	8.00	8.00	8.00	8.00
Circulating Water Price	Yuan/m^3	1	1	1	1	1	1
Fresh Water Cost	**Yuan/kg**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Fresh Water Consumption	kg/m^3 H_2	0.25	0.25	0.25	0.25	0.25	0.25
Fresh Water Price	Yuan/m^3	4	4	4	4	4	4
Demineralized Water Cost	**Yuan/kg**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**	**0.40**
Demineralized Water Consumption	kg/m^3 H_2	3.60	3.60	3.60	3.60	3.60	3.60
Demineralized Water Price	Yuan/m^3	10	10	10	10	10	10
Carbon Capture Cost	**Yuan/kg H_2**	**3.85**	**3.85**	**3.85**	**3.85**	**3.85**	**3.85**
Carbon Emission	kg/kg H_2	22.00	22.00	22.00	22.00	22.00	22.00
Carbon Capture Price	Yuan/kg CO2	0.18	0.18	0.18	0.18	0.18	0.18
Total Cost (Coal to Hydrogen)	**Yuan/kg**	**7.61**	**9.32**	**9.74**	**11.02**	**12.72**	**14.42**
Total Cost (Coal to Hydrogen CCS)	**Yuan/kg**	**11.46**	**13.17**	**13.59**	**14.87**	**16.57**	**18.27**

2) Cost Model of Hydrogen Production from Natural Gas

2.1) Key Assumptions

Natural gas-based hydrogen production technology is mature and low-cost, but it is associated with high carbon emissions. The key factor influencing the cost of natural gas-based hydrogen production technology is the price of natural gas. The author uses a 90,000 m^3/h hydrogen production plant scale as an example and analyzes the cost of hydrogen production by varying the price of natural gas. To comprehensively assess the economics of hydrogen production, this model currently excludes subsidy factors. However, it will serve as a reference for discussing policy and regulatory measures aimed at cost reduction in the future. The key assumptions of the model for the current time node are outlined below:

1) Hydrogen Production Scale: The scale of the hydrogen production plant is 90,000 m^3/hour, and the annual working time is 8,000 hours.
2) Hydrogen Density: 0.0893 kg/m^3 in a standard case.
3) Fixed Cost:

- Depreciation Cost: The construction cost amounts to 600 million yuan, with a salvage rate of 5%. Additionally, there is an annual repair cost equivalent to 3% of the construction cost. All of these expenses are depreciated over a 20-year period of operation.
- Labor Cost: Per capita salary of 80,000 yuan/person-year, with a staff of 108.
- Finance Cost: The loan amount is set at 70% of the construction cost, accruing an annual interest rate of 5%.

4) Variable Cost:

- Natural Gas Cost: Producing 1 $m^3$of hydrogen requires the consumption of approximately 0.34 m^3 of natural gas. The price of natural gas varies from 1.0 to 5.0 yuan/m^3.
- Other Material Cost: Producing 1 m^3 of hydrogen consumes 0.014 yuan worth of auxiliary materials.
- Fuel Power Cost: Producing 1 m^3 of hydrogen gas requires approximately 0.04 kWh of electricity, 2 kg of circulating water, 0.25 kg of fresh water, 2.2 kg of demineralized water, and 0.18 kg of by-product steam. The prices for these resources are as follows: electricity costs 0.56 yuan per kWh, circulating water costs 1 yuan/m^3, fresh water costs 4 yuan/m^3, demineralized water costs 10 yuan/m^3, and steam costs 100 yuan/ton.
- Carbon Capture Cost: Producing 1 kg of hydrogen results in 4.8 kg of carbon emissions. The cost of capturing 1 kg of CO_2 is 0.175 yuan.

2.2) Data Analysis

According to the model's measurements, the cost of hydrogen production from natural gas is positively correlated with the price of natural gas. Without considering subsidies, when the price of natural gas is 2.5 yuan/m^3, the cost of hydrogen production without considering carbon capture is 12.79 yuan/kg (representing 73% of the total natural gas cost for hydrogen production), and after considering carbon capture, the cost rises to 13.63 yuan/kg. If the natural gas price increases to 5.0 yuan/m^3, the cost of hydrogen production without carbon capture increases to 22.17 yuan/kg, while with carbon capture, it rises to 23.01 yuan/kg. Additionally, the product hydrogen shifts from gray hydrogen to blue hydrogen after carbon capture (refer to "Fig. 5.3.1.3 & Fig.

5.3.1.4 Sensitivity Calculation of Natural Gas-to-Hydrogen Cost to Natural Gas Price").

Fig. 5.3.1.3 Sensitivity Calculation of Natural Gas-to-Hydrogen Cost to Natural Gas Price

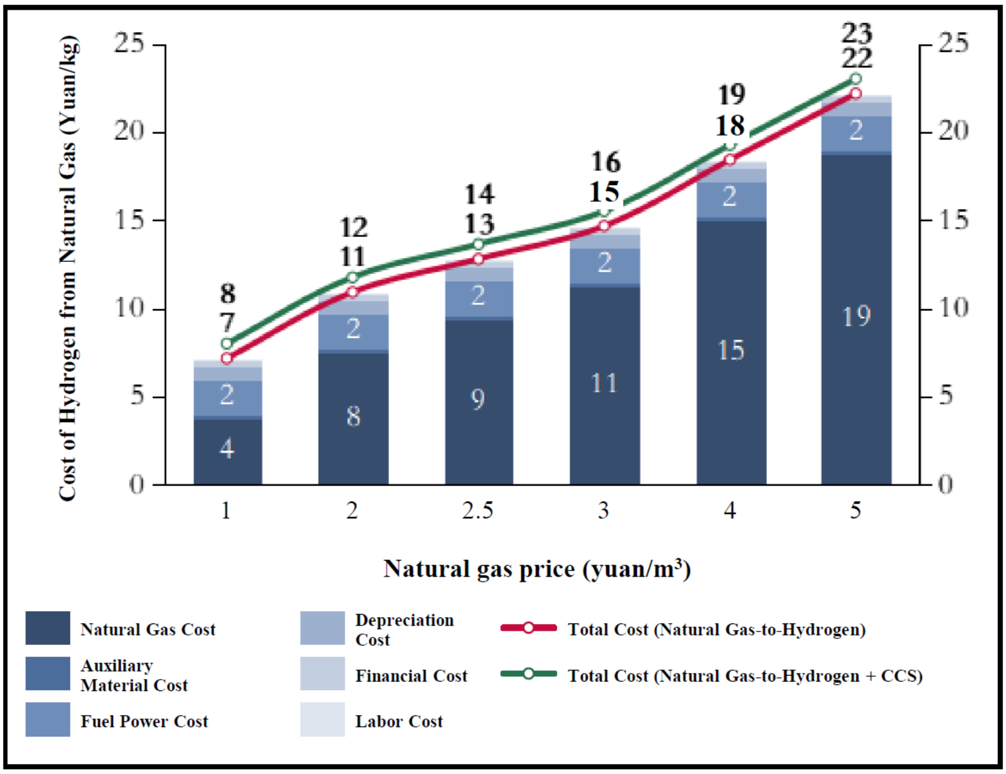
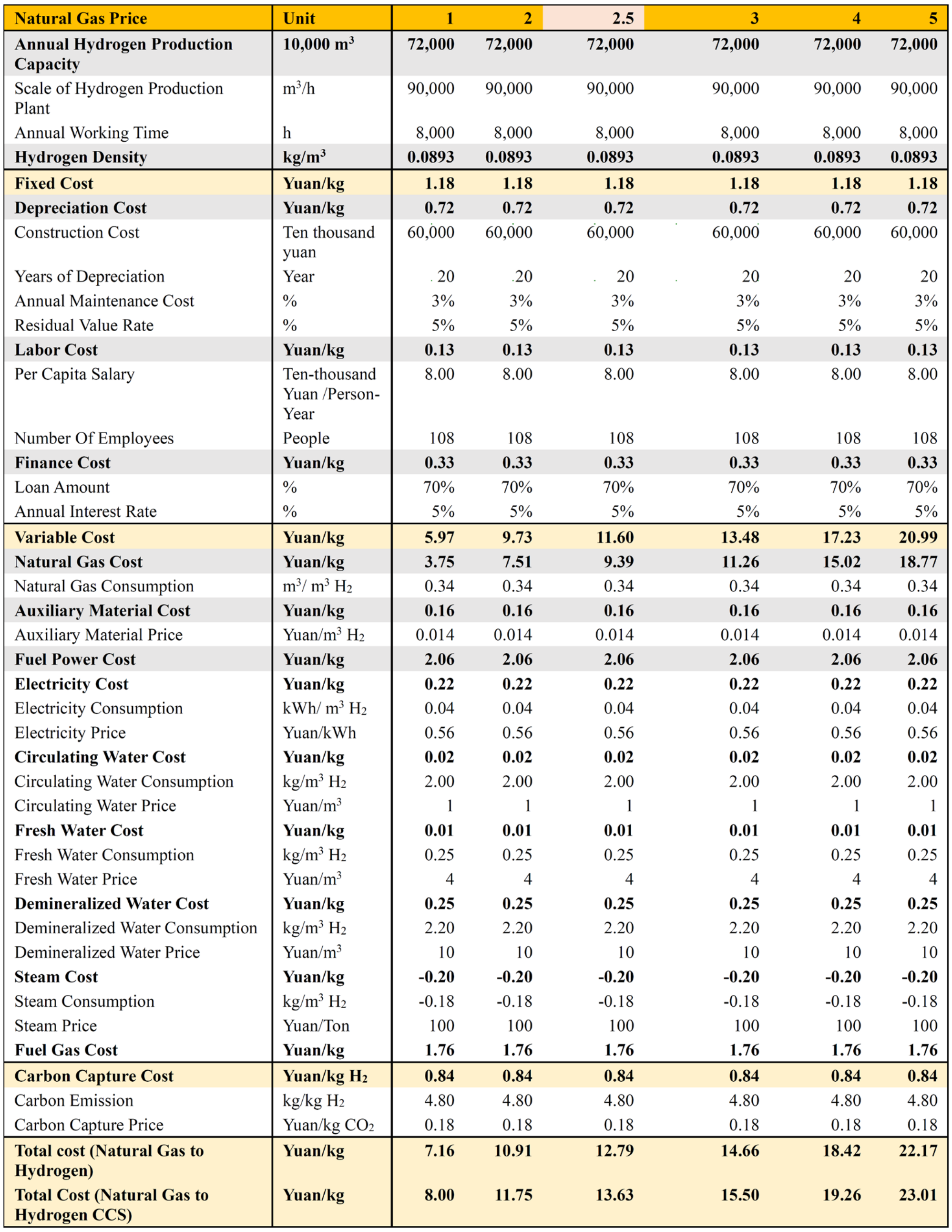


Fig. 5.3.1.4 Sensitivity Calculation of Natural Gas to Hydrogen Cost to Natural Gas Price



Natural Gas Price	Unit	1	2	2.5	3	4	5
Annual Hydrogen Production Capacity	**10,000 m³**	**72,000**	**72,000**	**72,000**	**72,000**	**72,000**	**72,000**
Scale of Hydrogen Production Plant	m³/h	90,000	90,000	90,000	90,000	90,000	90,000
Annual Working Time	h	8,000	8,000	8,000	8,000	8,000	8,000
Hydrogen Density	**kg/m³**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**
Fixed Cost	**Yuan/kg**	**1.18**	**1.18**	**1.18**	**1.18**	**1.18**	**1.18**
Depreciation Cost	**Yuan/kg**	**0.72**	**0.72**	**0.72**	**0.72**	**0.72**	**0.72**
Construction Cost	Ten thousand yuan	60,000	60,000	60,000	60,000	60,000	60,000
Years of Depreciation	Year	20	20	20	20	20	20
Annual Maintenance Cost	%	3%	3%	3%	3%	3%	3%
Residual Value Rate	%	5%	5%	5%	5%	5%	5%
Labor Cost	**Yuan/kg**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**	**0.13**
Per Capita Salary	Ten-thousand Yuan /Person-Year	8.00	8.00	8.00	8.00	8.00	8.00
Number Of Employees	People	108	108	108	108	108	108
Finance Cost	**Yuan/kg**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**	**0.33**
Loan Amount	%	70%	70%	70%	70%	70%	70%
Annual Interest Rate	%	5%	5%	5%	5%	5%	5%
Variable Cost	**Yuan/kg**	**5.97**	**9.73**	**11.60**	**13.48**	**17.23**	**20.99**
Natural Gas Cost	**Yuan/kg**	**3.75**	**7.51**	**9.39**	**11.26**	**15.02**	**18.77**
Natural Gas Consumption	m³/ m³ H_2	0.34	0.34	0.34	0.34	0.34	0.34
Auxiliary Material Cost	**Yuan/kg**	**0.16**	**0.16**	**0.16**	**0.16**	**0.16**	**0.16**
Auxiliary Material Price	Yuan/m³ H_2	0.014	0.014	0.014	0.014	0.014	0.014
Fuel Power Cost	**Yuan/kg**	**2.06**	**2.06**	**2.06**	**2.06**	**2.06**	**2.06**
Electricity Cost	**Yuan/kg**	**0.22**	**0.22**	**0.22**	**0.22**	**0.22**	**0.22**
Electricity Consumption	kWh/ m³ H_2	0.04	0.04	0.04	0.04	0.04	0.04
Electricity Price	Yuan/kWh	0.56	0.56	0.56	0.56	0.56	0.56
Circulating Water Cost	**Yuan/kg**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Circulating Water Consumption	kg/m³ H_2	2.00	2.00	2.00	2.00	2.00	2.00
Circulating Water Price	Yuan/m³	1	1	1	1	1	1
Fresh Water Cost	**Yuan/kg**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Fresh Water Consumption	kg/m³ H_2	0.25	0.25	0.25	0.25	0.25	0.25
Fresh Water Price	Yuan/m³	4	4	4	4	4	4
Demineralized Water Cost	**Yuan/kg**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
Demineralized Water Consumption	kg/m³ H_2	2.20	2.20	2.20	2.20	2.20	2.20
Demineralized Water Price	Yuan/m³	10	10	10	10	10	10
Steam Cost	**Yuan/kg**	**-0.20**	**-0.20**	**-0.20**	**-0.20**	**-0.20**	**-0.20**
Steam Consumption	kg/m³ H_2	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
Steam Price	Yuan/Ton	100	100	100	100	100	100
Fuel Gas Cost	**Yuan/kg**	**1.76**	**1.76**	**1.76**	**1.76**	**1.76**	**1.76**
Carbon Capture Cost	**Yuan/kg H_2**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**	**0.84**
Carbon Emission	kg/kg H_2	4.80	4.80	4.80	4.80	4.80	4.80
Carbon Capture Price	Yuan/kg CO_2	0.18	0.18	0.18	0.18	0.18	0.18
Total cost (Natural Gas to Hydrogen)	**Yuan/kg**	**7.16**	**10.91**	**12.79**	**14.66**	**18.42**	**22.17**
Total Cost (Natural Gas to Hydrogen CCS)	**Yuan/kg**	**8.00**	**11.75**	**13.63**	**15.50**	**19.26**	**23.01**

3) Cost Model of Hydrogen Production from Alkaline Water

3.1) Key Assumptions

The primary factor influencing the cost of hydrogen production from alkaline water is the price of electricity. The model analyzes the cost of hydrogen production by varying the price of electricity for a 1,000m^3/h alkaline water electrolyzer for hydrogen production. To comprehensively assess the economics of hydrogen production, this model currently excludes subsidy factors. However, it will serve as a reference for discussing policy and regulatory measures aimed at cost reduction in the future. The key assumptions of the model for the current time node are outlined below:

1) Scale of Hydrogen Production: For hydrogen production via alkaline water electrolysis, the plant size is assumed to be 1,000 m^3/hour, and the annual operating time is estimated to be 2,000 hours per year.

2) Hydrogen Density: 0.0893 kg/m^3 in a standard case.

3) Fixed Cost:

- Depreciation Cost: The equipment investment amounts to 7 million yuan, while civil construction and equipment installation cost 1.2 million yuan. These expenses are depreciated over a 20-year period with no salvage value.
- Labor Cost: Per capita salary of 80,000 yuan/person-year, with a staff of 4.
- Operation and Maintenance Cost: 1% of the equipment investment and civil construction and equipment installation costs.

4) Variable Cost:

- Electrolysis Cost: Producing 1 m^3 of hydrogen requires the consumption of 5.0 kWh of electricity. The price of electricity varies from 0.1 to 0.6 yuan/kWh.
- Other Material Cost: Producing 1 m^3 of hydrogen requires the consumption of 1 kg of raw water, 1 kg of cooling water, and 0.0004 kg of KOH. The cost of water is 3.5 yuan per ton, and the price of KOH is 10 yuan per kg.

3.2) Data Analysis

According to the model's measurements, the cost of hydrogen production from alkaline water is positively correlated with the price of electricity. Without considering subsidies, when the electricity price is 0.2 yuan/kWh, the cost of hydrogen production from alkaline water is 15.87 yuan/kg, representing 71% of the total cost for alkaline water hydrogen production. When the electricity price increases to 0.6 yuan/kWh, the cost of hydrogen production rises to 38.27 yuan/kg (refer to "Fig. 5.3.1.5 & Fig. 5.3.1.6 Sensitivity Calculation of Alkaline Water-to-Hydrogen Cost to Electricity Price").

Fig. 5.3.1.5 Sensitivity Calculation of Alkaline Water-to-Hydrogen Cost to Electricity Price

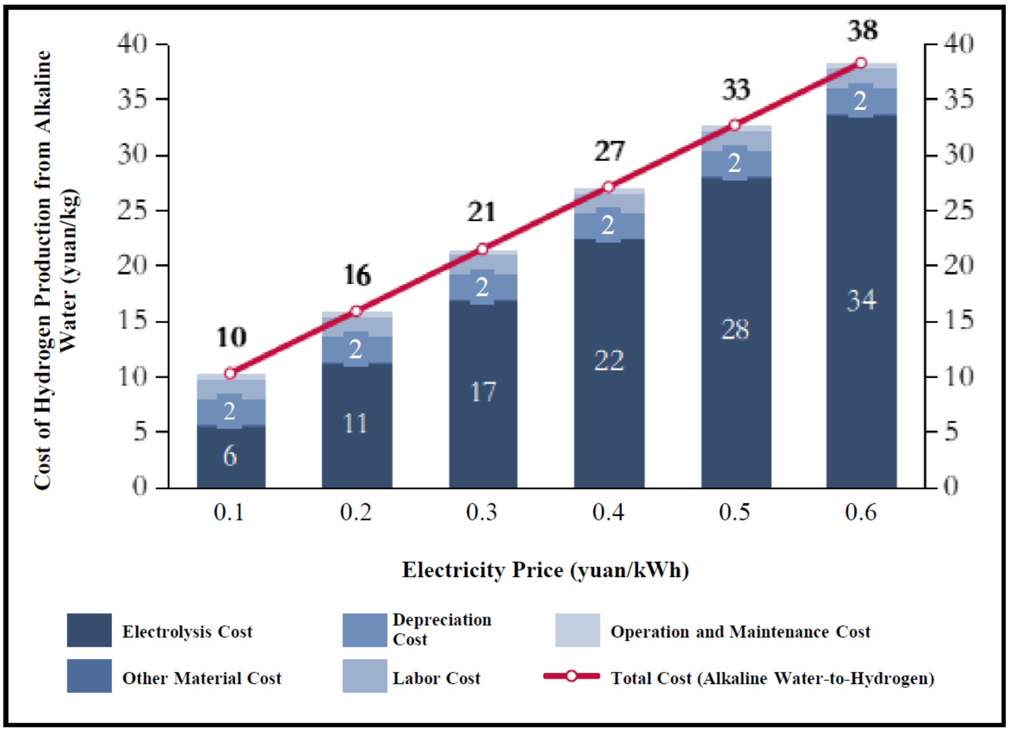


Fig. 5.3.1.6 Sensitivity Calculation of Alkaline Water-to-Hydrogen Cost to Electricity Price

Electricity Price	**Unit**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**
Annual Hydrogen Production Capacity	**10,000 m^3**	**200**	**200**	**200**	**200**	**200**	**200**
Scale of Hydrogen Production Plant	m3/h	1,000	1,000	1,000	1,000	1,000	1,000
Annual Working Time	h	2,000	2,000	2,000	2,000	2,000	2,000
Hydrogen Density	**kg/m^3**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**
Fixed Cost	**Yuan/kg**	**4.55**	**4.55**	**4.55**	**4.55**	**4.55**	**4.55**
Depreciation Cost	**Yuan/kg**	**2.30**	**2.30**	**2.30**	**2.30**	**2.30**	**2.30**
Equipment Investment	Ten thousand yuan	700	700	700	700	700	700
Civil Construction And Equipment Installation	Ten thousand yuan	120	120	120	120	120	120
Years of Depreciation	Year	20	20	20	20	20	20
Labor Cost	**Yuan/kg**	**1.79**	**1.79**	**1.79**	**1.79**	**1.79**	**1.79**
Per Capita Salary	Ten-thousand Yuan /Person-Year	8.00	8.00	8.00	8.00	8.00	8.00
Number of Employees	People	4	4	4	4	4	4
Operation and Maintenance Cost	**Yuan/kg**	**0.46**	**0.46**	**0.46**	**0.46**	**0.46**	**0.46**
Operation and Maintenance Cost	%	1%	1%	1%	1%	1%	1%
Variable Cost	**Yuan/kg**	**5.72**	**11.32**	**16.92**	**22.52**	**28.12**	**33.72**
Electrolysis Cost	**Yuan/kg**	**5.60**	**11.20**	**16.80**	**22.40**	**28.00**	**33.60**
Electricity Consumption	kWh/m^3 H_2	5.0	5.0	5.0	5.0	5.0	5.0
Other Material Cost	**Yuan/kg**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**
Pure Water Cost	**Yuan/kg**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**
Pure Water Consumption	kg/m^3 H_2	1	1	1	1	1	1
Pure Water Price	Yuan/m^3	3.50	3.50	3.50	3.50	3.50	3.50
Cooling Water Cost	**Yuan/kg**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**
Cooling Water Consumption	kg/m^3 H_2	1	1	1	1	1	1
Cooling Water Price	Yuan/m^3	3.50	3.50	3.50	3.50	3.50	3.50
KOH Cost	**Yuan/kg**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**
KOH Consumption	kg/m^3 H_2	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
SSM	Yuan/kg	10	10	10	10	10	10
Total Cost (Alkaline Water to Hydrogen)	**Yuan/kg**	**10.27**	**15.87**	**21.47**	**27.07**	**32.67**	**38.27**

4) Cost Model of Hydrogen Production from PEM

4.1) Key Assumptions

The primary factor influencing the cost of PEM-based hydrogen production is the price of electricity. The model analyzes the cost of hydrogen production by varying the price of electricity for a 1,000m^3/h alkaline water electrolyzer for hydrogen production. To comprehensively assess the economics of hydrogen production, this model currently excludes subsidy factors. However, it will serve as a reference for discussing policy and regulatory measures aimed at cost reduction in the future. The key assumptions of the model for the current time node are outlined below:

5) Hydrogen Production Scale: PEM is used to produce hydrogen, the plant size is 1,000m^3/h, and the annual working time is 2,000 hours.

6) Hydrogen Density: 0.0893 kg/m^3 in a standard case.

7) Fixed Cost:

- Depreciation Cost: The equipment investment amounts to 25 million yuan, while civil construction and equipment installation cost 1.5 million yuan. These expenses are depreciated over a 20-year period with no salvage value.
- Labor Cost: Per capita salary of 80,000 yuan/person-year, with a staff of 4.
- Operation and Maintenance Cost: 0.3% of the equipment investment and civil construction and equipment installation costs.

8) Variable Cost:

- Electrolysis Cost: Producing 1 m^3 of hydrogen requires the consumption of 4.5 kWh of electricity. The price of electricity varies from 0.1 to 0.6 yuan/kWh.
- Other Material Cost: Producing 1m^3 of hydrogen requires the consumption of 1 kg of raw water and 1 kg of cooling water. The cost of water is 3.5 yuan per ton.

4.2) Data Analysis

According to the model's measurements, the cost of PEM hydrogen production is positively correlated with the electricity price. Without considering subsidies, when the electricity price is 0.2 yuan/kWh, the cost of hydrogen production is 19.83 yuan/kg, representing 51% of the total PEM hydrogen production cost. When the electricity price increases to 0.6 yuan/kWh, the cost of hydrogen production rises to 39.99 yuan/kg (refer to "Fig. 5.3.1.7 & Fig. 5.3.1.8 Sensitivity Calculation of PEM-to-Hydrogen Cost to Electricity Price" and "Fig. 5.3.1.9 Comparison of Sensitivity Calculation of Alkaline Water vs PEM-to-Hydrogen Cost to Electricity Price").

Therefore, finding ways to further reduce the cost of hydrogen production is crucial for the potential widespread application of hydrogen fuel cell vehicles.

Fig. 5.3.1.7 Sensitivity Calculation of PEM-to-Hydrogen Cost to Electricity Price

Electricity Price	**Unit**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**
Annual Hydrogen Production Capacity	**10,000 m^3**	**200**	**200**	**200**	**200**	**200**	**200**
Scale of hydrogen production plant	m^3/h	1,000	1,000	1,000	1,000	1,000	1,000
Annual working time	h	2,000	2,000	2,000	2,000	2,000	2,000
Hydrogen density	**kg/m^3**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**
Fixed Cost	**Yuan/kg**	**9.67**	**9.67**	**9.67**	**9.67**	**9.67**	**9.67**
Depreciation Cost	**Yuan/kg**	**7.42**	**7.42**	**7.42**	**7.42**	**7.42**	**7.42**
Equipment Investment	Ten thousand yuan	2,500	2,500	2,500	2,500	2,500	2,500
Civil Construction And Equipment Installation	Ten thousand yuan	150	150	150	150	150	150
Years of Depreciation	Year	20	20	20	20	20	20
Labor Cost	**Yuan/kg**	**1.79**	**1.79**	**1.79**	**1.79**	**1.79**	**1.79**
Per Capita Salary	Ten-thousand Yuan /Person-Year	8.00	8.00	8.00	8.00	8.00	8.00
Number of Employees	People	4	4	4	4	4	4
Operation and Maintenance Cost	**Yuan/kg**	**0.46**	**0.46**	**0.46**	**0.46**	**0.46**	**0.46**
Operation and Maintenance Cost	%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Variable Cost	**Yuan/kg**	**5.12**	**10.16**	**15.20**	**20.24**	**25.28**	**30.32**
Electrolysis Cost	**Yuan/kg**	**5.04**	**10.08**	**15.12**	**20.16**	**25.20**	**30.24**
Electricity Consumption	kWh/ m^3 H_2	4.5	4.5	4.5	4.5	4.5	4.5
Other Material Cost	**Yuan/kg**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**
Pure Water Cost	**Yuan/kg**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**
Pure Water Consumption	kg/m^3 H_2	1	1	1	1	1	1
Pure Water Price	Yuan/m^3	3.50	3.50	3.50	3.50	3.50	3.50
Cooling Water Cost	**Yuan/kg**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**
Cooling Water Consumption	kg/m^3 H_2	1	1	1	1	1	1
Cooling Water Price	Yuan/m^3	3.50	3.50	3.50	3.50	3.50	3.50
Total Cost (PEM Hydrogen)	**Yuan/kg**	**14.79**	**19.83**	**24.87**	**29.91**	**34.95**	**39.99**

Fig. 5.3.1.8 Sensitivity Calculation of PEM-to-Hydrogen Cost to Electricity Price

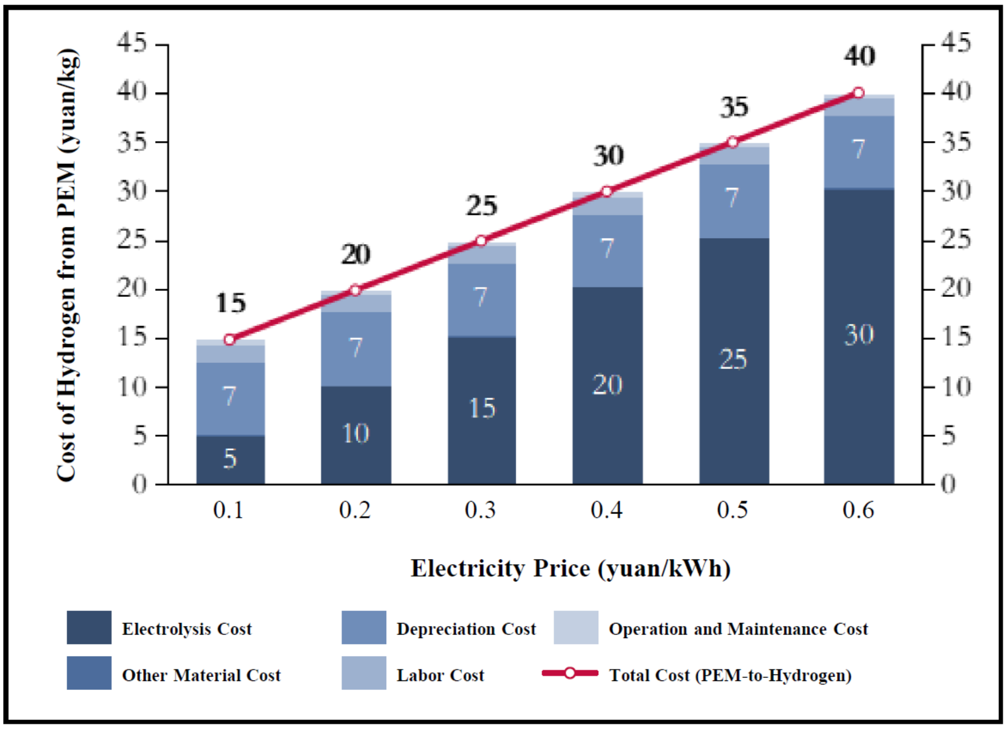
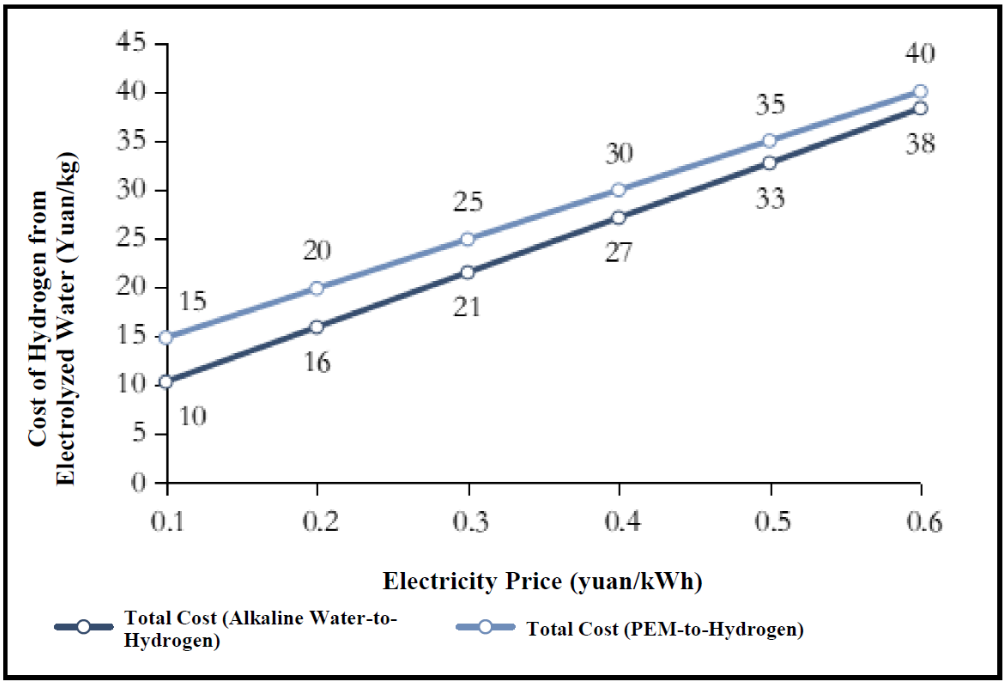


Fig. 5.3.1.9 Comparison of Sensitivity Calculation of Alkaline Water vs PEM-to-Hydrogen Cost to Electricity Price



5.3.2 Hydrogen Storage and Transportation

Hydrogen storage and transportation are currently centered around tube trailers. However, limitations exist due to transportation mass and radius. The future trend leans towards large-scale, long-distance storage and transportation via pipeline networks and liquid hydrogen tanker trucks.

1) Cost Model of Hydrogen Transportation by Tube Trailers

1.1) Key Assumptions

Currently, China predominantly utilizes tube trailers for hydrogen storage and transportation, with costs closely tied to the distance from the hydrogen source and the constraints of the trailer's operating pressure. Currently, China is constrained by national standards, with tube trailers limited to a maximum working pressure of 20 MPa. However, overseas, 50 MPa hydrogen tube trailers have been introduced, allowing for more hydrogen to be stored in the same volume of tube bundle and significantly increasing the loading capacity of hydrogen per vehicle. This model examines the cost of hydrogen storage and transportation by varying the distance from the hydrogen source, using examples of both 20 MPa and 50 MPa tube trailers. To comprehensively evaluate the economics of hydrogen storage and transportation, this model does not currently incorporate subsidy factors. However, subsidies may be discussed later as a policy adjustment tool to guide efforts aimed at reducing costs. The key assumptions of the model for the current time node are outlined below:

1) Hydrogen Transportation Mass: The 20 MPa tube trailer is fully loaded with 350 kg of hydrogen, while the 50 MPa tube trailer can carry up to 1,200 kg of hydrogen when fully loaded. Both trailers have a residual hydrogen rate of 20% in the tube bundle.

2) Number of Round Trips: The trailer operates for 15 hours a day, 365 days a year, with an average refueling and unloading time of 5 hours and an average speed of 50 km/hour.

3) Fixed Cost:

- Depreciation of Equipment: The investment for the headstock is 400,000 yuan per vehicle, and for the tube bundles, they are 1,000,000 yuan/vehicle. Both investments are depreciated over 10 years of operation.
- Labor Cost: The per capita salary is 100,000 yuan per person-year, with a total of 4 staff members, including 2 drivers and 2 loaders and unloaders.
- Vehicle Insurance: 10,000 yuan/year.

4) Variable Cost:

- Fuel Cost: The trailer consumes 25 liters of fuel per 100 km, and the price of diesel is 6.5 yuan per liter.
- Vehicle Maintenance Fee: 0.3 yuan/km.
- Road Toll: 0.6 yuan/km.
- Electricity Cost of Hydrogen Compression: The hydrogen compression consumes 1 kWh of electricity per kg, and the electricity price is 0.6 yuan per kWh.

1.2) Data Analysis

According to the model's measurements, the cost of transporting hydrogen in a tube trailer is positively correlated with the distance of the hydrogen source and negatively correlated with the working pressure. Without considering subsidies, when the transportation distance is 100 km, the hydrogen storage and transportation cost for a 20 MPa tube trailer is 7.79 yuan/kg, while for a 50 MPa trailer, it is 2.70 yuan/kg. When the transportation distance is increased to 500 km, the hydrogen storage and transportation cost for a 20 MPa tube trailer rises to 20.38 yuan/kg, and for a 50 MPa trailer, it increases to 6.37 yuan/kg. It is evident that the cost of hydrogen transportation in the tube trailer decreases with the increase in the working pressure of the tube bundle. Considering economic factors, it is an industry trend to increase the hydrogen storage pressure of cylinders in tube trailers as technology allows.

The cost of storage and transportation for tube trailers increases significantly as the distance to the hydrogen source increases, with labor and fuel costs being the two primary factors driving up the cost. The number of daily round trips made by tube trailers decreases as the distance to the hydrogen source increases. Specifically, when the distance to the source is less than 50 km, the trailers make two round trips per day. For distances between 50 km and 250 km, they make one round trip per day, and for distances between 300 km and 500 km, they make 0.5 round trips per day. As the daily round trip distance decreases, the labor cost and equipment depreciation per unit mass of hydrogen storage and transportation increases significantly. In addition, the fuel cost rises as the distance to the hydrogen source increases.

According to the model, when the distance to the hydrogen source exceeds 250 km, the cost of hydrogen storage and transportation in tube trailers increases significantly. Therefore, tube trailers are generally used for short-distance hydrogen transportation up to 250 km (refer to "Fig. 5.3.2.1 & Fig. 5.3.2.4 Sensitivity Calculation of 20 MPa Tube Trailer Storage and Transportation Cost to Distance from Hydrogen Source", "Fig. 5.3.2.2 & Fig. 5.3.2.5 Sensitivity Calculation of 50 MPa Tube Trailer Storage and Transportation Cost to Distance from Hydrogen Source", and "Fig. 5.3.2.3 Comparison of Sensitivity Calculation of 20 MPa vs 50 MPa Tube Trailer Storage and Transportation Cost to Distance from Hydrogen Source").

Fig. 5.3.2.1 Sensitivity Calculation of 20 MPa Tube Trailer Storage and Transportation Cost to Distance from Hydrogen Source

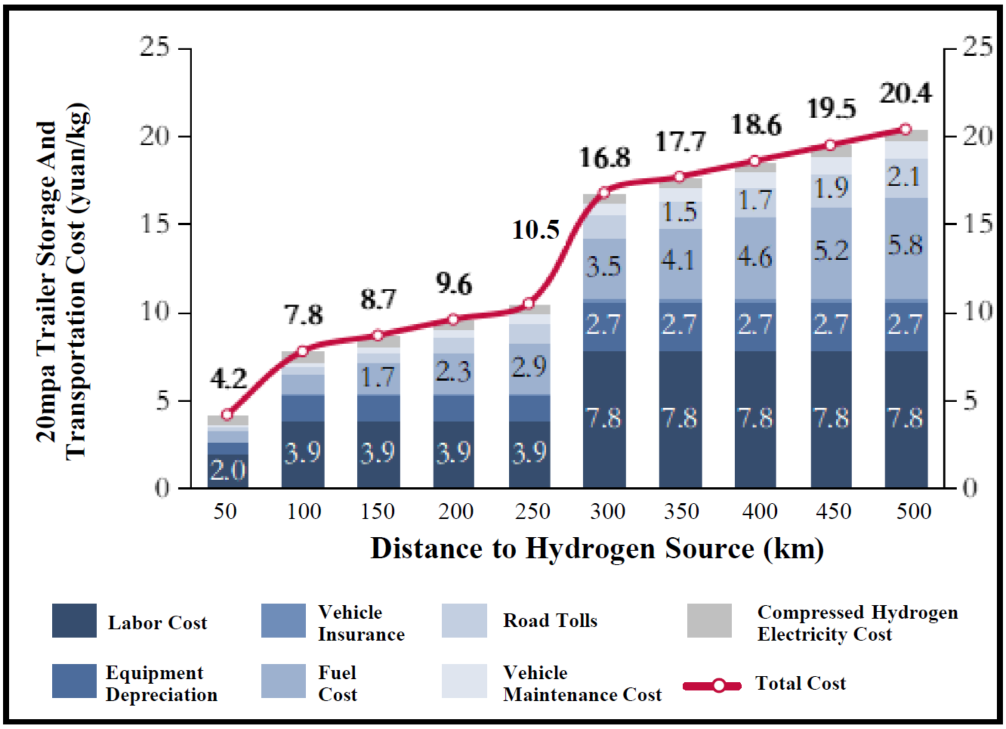


Fig. 5.3.2.2 Sensitivity Calculation of 50 MPa Tube Trailer Storage and Transportation Cost to Distance from Hydrogen Source

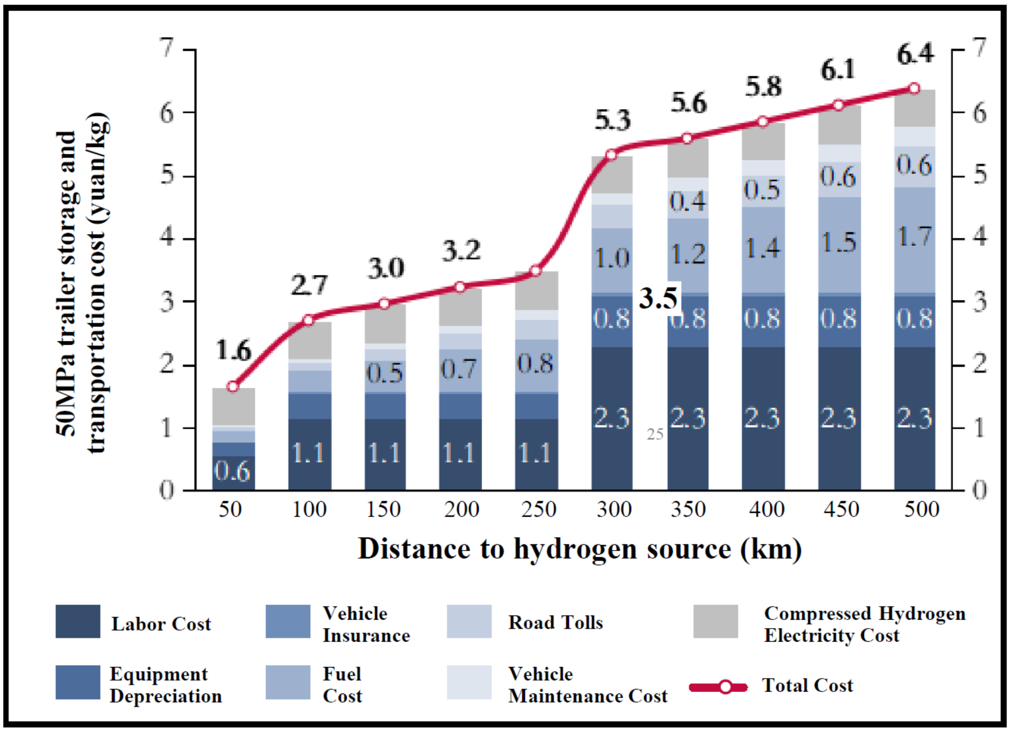


Fig. 5.3.2.3 Comparison of Sensitivity Calculation of 20 MPa vs 50 MPa Tube Trailer Storage and Transportation Cost to Distance from Hydrogen Source

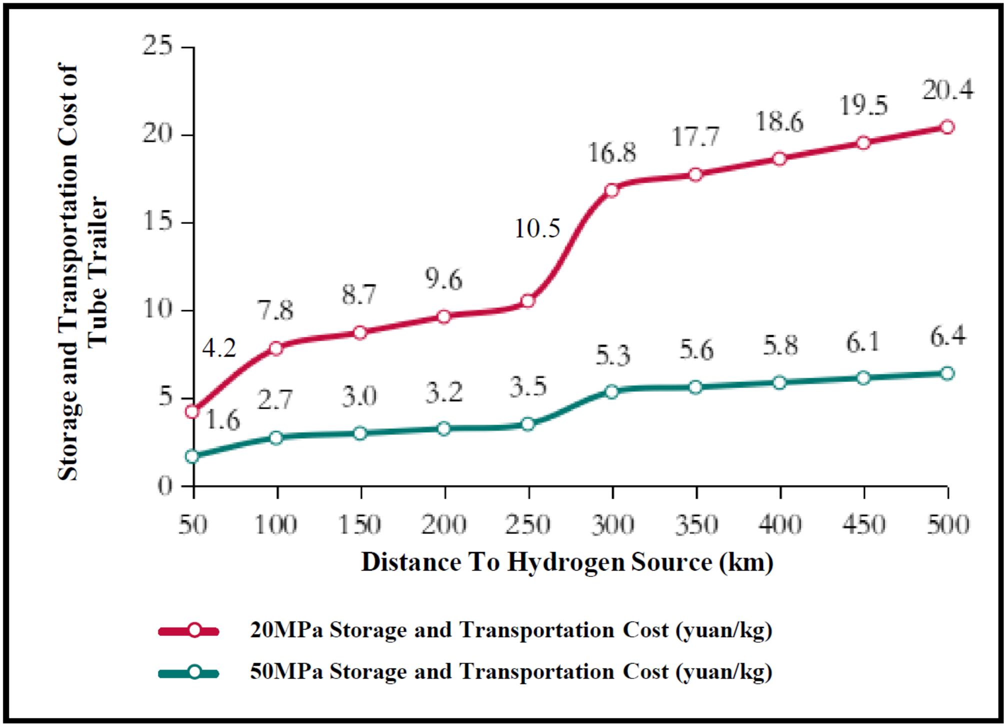


Fig. 5.3.2.4 Sensitivity Calculation of 20 Mpa Tube Trailer Storage and Transportation Cost to Distance from Hydrogen Source

Distance to Hydrogen Source	**Unit**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
Mass of Hydrogen Transported in a Single Trip	**kg**	**280**	**280**	**280**	**280**	**280**	**280**	**280**	**280**	**280**	**280**
Trailer Loading Capacity (20MPa)	kg	350	350	350	350	350	350	350	350	350	350
Tube Bundle Hydrogen Residual Rate	%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Daily Round Trips	**Time**	**2.0**	**1.0**	**1.0**	**1.0**	**1.0**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Daily Working Time	h	15	15	15	15	15	15	15	15	15	15
Length of Trailer Loading and Unloading of Hydrogen	h	5	5	5	5	5	5	5	5	5	5
Average Trailer Speed	km/h	50	50	50	50	50	50	50	50	50	50
Number of Working Days per Year	**Day**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**
Fixed Cost	**Yuan/kg**	**2.69**	**5.38**	**5.38**	**5.38**	**5.38**	**10.76**	**10.76**	**10.76**	**10.76**	**10.76**
Depreciation of Equipment	**Yuan/kg**	**0.68**	**1.37**	**1.37**	**1.37**	**1.37**	**2.74**	**2.74**	**2.74**	**2.74**	**2.74**
Headstock Price	Ten-thousand Yuan/vehicle	40	40	40	40	40	40	40	40	40	40
Tube Bundle Price	Ten-thousand Yuan/vehicle	100	100	100	100	100	100	100	100	100	100
Years of Depreciation	Year	10	10	10	10	10	10	10	10	10	10
Labor Cost	**Yuan/kg**	**1.96**	**3.91**	**3.91**	**3.91**	**3.91**	**7.83**	**7.83**	**7.83**	**7.83**	**7.83**
Per Capita Salary	Ten-thousand Yuan /Person-Year	10	10	10	10	10	10	10	10	10	10
Number of Employees	People	4	4	4	4	4	4	4	4	4	4
Vehicle Insurance	**Yuan/kg**	**0.05**	**0.10**	**0.10**	**0.10**	**0.10**	**0.20**	**0.20**	**0.20**	**0.20**	**0.20**
Vehicle Insurance Cost	Ten-thousand Yuan/Year	1	1	1	1	1	1	1	1	1	1
Variable Cost	Yuan/kg	**1.50**	**2.40**	**3.31**	**4.21**	**5.11**	**6.01**	**6.91**	**7.81**	**8.72**	**9.62**
Fuel Cost	**Yuan/kg**	**0.58**	**1.16**	**1.74**	**2.32**	**2.90**	**3.48**	**4.06**	**4.64**	**5.22**	**5.80**
Fuel Consumption per 100Km	L	25	25	25	25	25	25	25	25	25	25
Diesel Fuel Price	Yuan/L	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Vehicle Maintenance Cost	**Yuan/kg**	**0.11**	**0.21**	**0.32**	**0.43**	**0.54**	**0.64**	**0.75**	**0.86**	**0.96**	**1.07**
Vehicle Maintenance Cost	Yuan /km	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Road Toll	**Yuan/kg**	**0.21**	**0.43**	**0.64**	**0.86**	**1.07**	**1.29**	**1.50**	**1.71**	**1.93**	**2.14**
Road Toll	Yuan /km	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Compressed Hydrogen Electricity Cost	**Yuan/kg**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**
Compressed Hydrogen Electricity Consumption	kWh/kg	1	1	1	1	1	1	1	1	1	1
Electricity Price	Yuan/kWh	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total Cost	**Yuan/kg**	**4.19**	**7.79**	**8.69**	**9.59**	**10.49**	**16.77**	**17.68**	**18.58**	**19.48**	**20.38**

Fig. 5.3.2.5 Sensitivity Calculation of 50 Mpa Tube Trailer Storage and Transportation Cost to Distance from Hydrogen Source

Distance to Hydrogen Source	**Unit**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**
Mass of Hydrogen Transported in a Single Trip	**kg**	**960**	**960**	**960**	**960**	**960**	**960**	**960**	**960**	**960**	**960**
Trailer Loading Capacity (50MPa)	kg	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200
Tube Bundle Hydrogen Residual Rate	%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Daily Round Trips	**Time**	**2.0**	**1.0**	**1.0**	**1.0**	**1.0**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Daily Working Time	h	15	15	15	15	15	15	15	15	15	15
Length of Trailer Loading and Unloading of Hydrogen	h	5	5	5	5	5	5	5	5	5	5
Average Trailer Speed	km/h	50	50	50	50	50	50	50	50	50	50
Number of Working Days per Year	**Day**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**
Fixed Cost	**Yuan/kg**	**0.78**	**1.57**	**1.57**	**1.57**	**1.57**	**3.14**	**3.14**	**3.14**	**3.14**	**3.14**
Depreciation of Equipment	**Yuan/kg**	**0.20**	**0.40**	**0.40**	**0.40**	**0.40**	**0.80**	**0.80**	**0.80**	**0.80**	**0.80**
Headstock Price	Ten-thousand Yuan/vehicle	40	40	40	40	40	40	40	40	40	40
Tube Bundle Price	Ten-thousand Yuan/vehicle	100	100	100	100	100	100	100	100	100	100
Years of Depreciation	Year	10	10	10	10	10	10	10	10	10	10
Labor Cost	**Yuan/kg**	**0.57**	**1.14**	**1.14**	**1.14**	**1.14**	**2.28**	**2.28**	**2.28**	**2.28**	**2.28**
Per Capita Salary	Ten-thousand Yuan /Person-Year	10	10	10	10	10	10	10	10	10	10
Number of Employees	People	4	4	4	4	4	4	4	4	4	4
Vehicle Insurance	**Yuan/kg**	**0.01**	**0.03**	**0.03**	**0.03**	**0.03**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**
Vehicle Insurance Cost	Ten-thousand Yuan/Year	1	1	1	1	1	1	1	1	1	1
Variable Cost	Yuan/kg	**0.86**	**1.13**	**1.39**	**1.65**	**1.92**	**2.18**	**2.44**	**2.70**	**2.97**	**3.23**
Fuel Cost	**Yuan/kg**	**0.17**	**0.34**	**0.51**	**0.68**	**0.85**	**1.02**	**1.18**	**1.35**	**1.52**	**1.69**
Fuel Consumption Per 100Km	L	25	25	25	25	25	25	25	25	25	25
Diesel Fuel Price	Yuan/L	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Vehicle Maintenance Cost	**Yuan/kg**	**0.03**	**0.06**	**0.09**	**0.13**	**0.16**	**0.19**	**0.22**	**0.25**	**0.28**	**0.31**
Vehicle Maintenance Cost	Yuan /km	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Road Toll	**Yuan/kg**	**0.06**	**0.13**	**0.19**	**0.25**	**0.31**	**0.38**	**0.44**	**0.50**	**0.56**	**0.63**
Road Toll	Yuan /km	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Compressed Hydrogen Electricity Cost	**Yuan/kg**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**
Compressed Hydrogen Electricity Consumption	kWh/kg	1	1	1	1	1	1	1	1	1	1
Electricity Price	Yuan/kWh	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total Cost	**Yuan/kg**	**1.65**	**2.70**	**2.96**	**3.22**	**3.48**	**5.32**	**5.58**	**5.84**	**6.11**	**6.37**

Due to the limitations in scale and distance for hydrogen transportation via tube trailers, the current storage and transportation stageposes a bottleneck for the large-scale promotion of hydrogen energy. Promoting large-scale and long-distance hydrogen transportation, as well as further reducing the cost of hydrogen storage and transportation, are crucial factors for advancing the application of hydrogen fuel cell vehicles.

2) Cost Model of Hydrogen Transportation by Pipeline

2.1) Key Assumptions

Hydrogen transportation by pipeline represents the future development trend, as it is more suitable for large-scale and long-distance storage and transportation. Its cost is directly linked to the transportation distance. This model utilizes hydrogen pipelines as an example and analyzes the cost of hydrogen storage and transportation by varying the transportation distance. To comprehensively evaluate the economics of hydrogen storage and transportation, this model does not currently incorporate subsidy factors. However, subsidies may be discussed later as a policy-adjustment tool to guide efforts aimed at reducing costs. The key assumptions of the model for the current time node are outlined below:

1） Fixed Cost:

- Pipeline Depreciation: The total investment for pipeline construction is 5.84 million yuan per kilometer. The annual hydrogen transmission capacity is 100,400 tons, assuming 100% capacity utilization. The transport hydrogen loss rate is 8%. Depreciation is calculated based on a 20-year operating period.

- Maintenance Cost: The direct and indirect maintenance cost of the pipeline gas distribution station is calculated at 15% of the total investment.

2) Variable Cost:

- Electricity Cost of Hydrogen Compression: The hydrogen compression consumes 1 kWh of electricity per kg, and the electricity price is 0.6 yuan per kWh.

2.2) Data Analysis

According to the model's measurements, the cost of hydrogen delivery by pipeline is positively correlated with the transportation distance. Without considering subsidies and assuming a capacity utilization rate of 100%, pipeline hydrogen transmission generally offers more economic advantages compared to hydrogen transported by tube trailers. When the transportation distance is 50 kilometers, pipeline hydrogen costs 0.78 yuan/kg, while tube trailer hydrogen costs 4.19 yuan/kg, resulting in a cost difference of 5.4 times. When the transportation distance increases to 500 kilometers, pipeline hydrogen costs 2.42 yuan/kg, whereas tube trailer hydrogen costs 20.38 yuan/kg, leading to a cost difference of 8.4 times. Therefore, pipeline hydrogen transportation is better suited for large-scale and long-distance hydrogen transportation applications. With increasing transportation distance, the rise in pipeline hydrogen transportation cost primarily stems from pipeline depreciation and maintenance expenses (refer to "Fig. 5.3.2.1 & Fig. 5.3.2.2 Sensitivity Calculation of Pipeline Hydrogen Transportation Cost to Distance from Hydrogen Source").

Fig. 5.3.2.1 Sensitivity Calculation of Pipeline Hydrogen Transportation Cost to Distance from Hydrogen Source

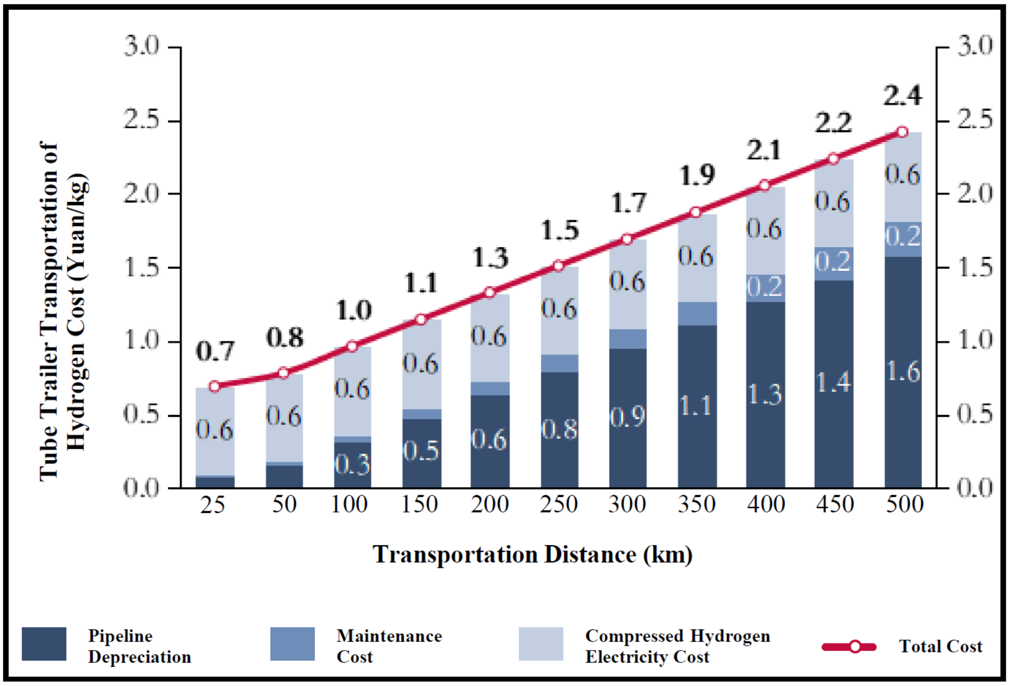


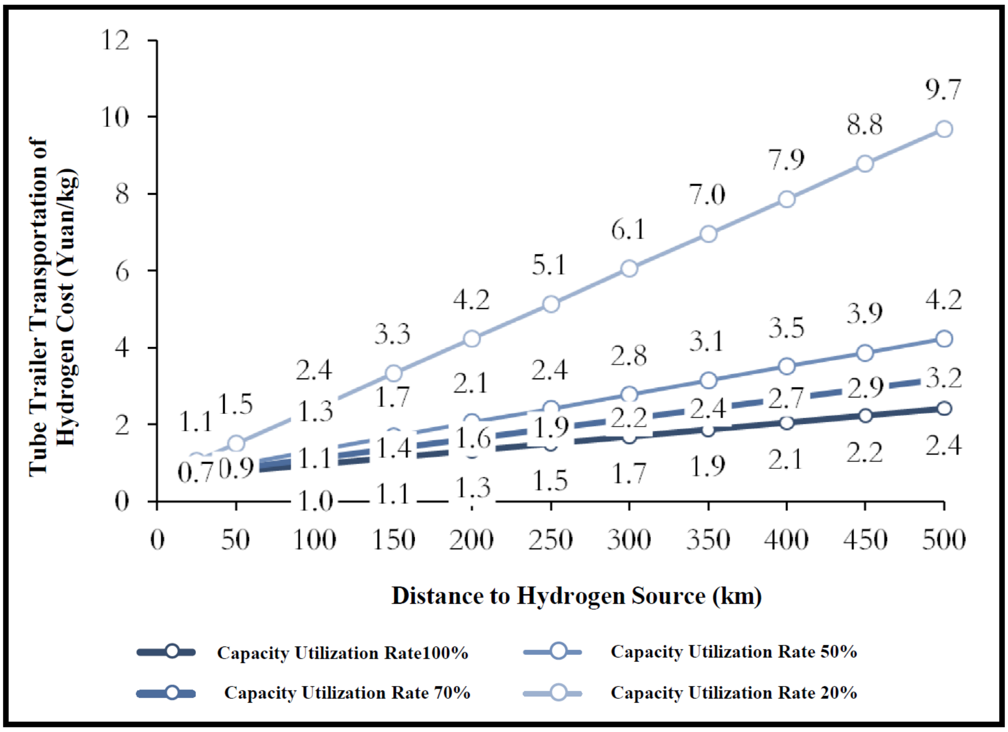
Fig. 5.3.2.2 Sensitivity Calculation of Pipeline Hydrogen Transportation Cost to Distance from Hydrogen Source

Transportation Distance	Unit	25	50	100	150	200	250	300	350	400	450	500
Annual Hydrogen Transportation Quality	**Ten thousand tons**	**10.04**	**10.04**	**10.04**	**10.04**	**10.04**	**10.04**	**10.04**	**10.04**	**10.04**	**10.04**	**10.04**
Annual Hydrogen Transfer Capacity	Ten thousand tons	10.04	10.04	10.04	10.04	10.04	10.04	10.04	10.04	10.04	10.04	10.04
Capacity Utilization	%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Fixed Cost	**Yuan/kg**	**0.09**	**0.18**	**0.36**	**0.55**	**0.73**	**0.91**	**1.09**	**1.27**	**1.45**	**1.64**	**1.82**
Tube Depreciation	**Yuan/kg**	**0.08**	**0.16**	**0.32**	**0.47**	**0.63**	**0.79**	**0.95**	**1.11**	**1.26**	**1.42**	**1.58**
Total Investment	Ten thousand Yuan/km	584	584	584	584	584	584	584	584	584	584	584
Loss Rate of Hydrogen Transportation	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Tube Life	Year	20	20	20	20	20	20	20	20	20	20	20
Maintenance Cost	**Yuan/kg**	**0.01**	**0.02**	**0.05**	**0.07**	**0.09**	**0.12**	**0.14**	**0.17**	**0.19**	**0.21**	**0.24**
Maintenance Rate	%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%
Variable Cost	**Yuan/kg**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**
Compressed Hydrogen Electricity Cost	**Yuan/kg**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**
Hydrogen Compression Power Consumption	kWh/kg	1	1	1	1	1	1	1	1	1	1	1
Electricity Price	Yuan/kWh	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total Cost	**Yuan/kg**	**0.69**	**0.78**	**0.96**	**1.15**	**1.33**	**1.51**	**1.69**	**1.87**	**2.05**	**2.24**	**2.42**

Nonetheless, the cost of pipeline hydrogen transportation is heavily influenced by downstream demand, particularly the capacity utilization rate. When the transportation distance is 100 km, at a capacity utilization rate of 100%, the cost of pipeline hydrogen transportation is only 0.96 yuan/kg. However, when the capacity utilization rate drops to 20%, the cost of pipeline hydrogen delivery rises to 2.42 yuan/kg (refer to "Fig. 5.3.2.3 Sensitivity Calculation of Pipeline Hydrogen Transportation Cost to Capacity Utilization Rate"). Currently, in China, there are insufficient downstream hydrogen refueling stations and they are scattered. Consequently, pipeline hydrogen transportation does not offer the most optimal economic solution. In the future, as the hydrogen energy industry gradually matures and hydrogen refueling stations become more widespread, the capacity utilization rate of pipeline hydrogen transportation will continue to improve. This will further enhance its cost advantage. Taking into account the challenges posed by "hydrogen embrittlement" in pipeline hydrogen transportation, as well as the complexities of separation technology and the risk of hydrogen leakage associated with blending hydrogen in natural gas pipelines, the author believes that it will be challenging for pipeline hydrogen transportation to become the mainstream mode of hydrogen storage and transportation in the short to medium term.

It is noteworthy that the cost of pipeline hydrogen transportation is significantly influenced by the scale of hydrogen transportation. In the future, as the scale of hydrogen transportation continues to increase, it is anticipated that the cost of pipeline hydrogen transportation will be further reduced.[34]

Fig. 5.3.2.3 Sensitivity Calculation of Pipeline Hydrogen Transportation Cost to Capacity Utilization Rate



3) Cost Model of Hydrogen Transportation by Liquid Hydrogen Tanker Truck

3.1) Key Assumptions

Liquid hydrogen tanker truck storage and transportation have been widely implemented in foreign countries, primarily for military applications in China. The cost of liquid hydrogen tanker truck storage and transportation is closely linked to the distance of the hydrogen source. This model utilizes liquid hydrogen tanker trucks as an example and analyzes the cost of hydrogen storage and transportation by varying the distance of the hydrogen source. To comprehensively evaluate the economics of hydrogen storage and transportation, this model does not currently incorporate subsidy factors. However, subsidies may be discussed later as a policy adjustment tool to guide efforts aimed at reducing costs. The key assumptions of the model for the current time node are outlined below:

1） Hydrogen Transportation Mass: 4,000 kg loading capacity of hydrogen tanker truck.

2） Number of Round Trips: The tanker trucks operate for 15 hours a day, 365 days a year, with an average refueling and unloading time of 6.5 hours and an average speed of 50 km/hour.

3） Fixed Cost:

- Depreciation of Equipment: The price of a liquid hydrogen tanker truck is 3.5 million yuan per vehicle, depreciated over an operational period of 10 years.
- Labor Cost: The per capita salary is 100,000 yuan per person-year, with a total of 4 staff members, including 2 drivers and 2 loaders and unloaders.
- Vehicle Insurance: 10,000 yuan/year.

4） Variable Cost:

- Fuel Cost: The trailer consumes 25 liters of fuel per 100 km, and the price of diesel is 6.5 yuan per liter.
- Vehicle Maintenance Fee: 0.3 yuan/km.
- Road toll: 0.6 yuan/km.
- Electricity Cost of Hydrogen Liquefaction: The electricity consumption for hydrogen liquefaction is 11 kWh/kg, and the electricity price is 0.6 yuan/kWh.

3.2) Data Analysis

According to the model's measurements, the sensitivity of the storage and transportation cost of liquid hydrogen tanker trucks to changes in the distance from the hydrogen source is low. This is primarily due to the fact that electricity consumption for hydrogen liquefaction comprises more than 80% of the total cost, with the remaining costs not accounting for a significant proportion. The electricity consumption of hydrogen liquefaction is directly linked to the hydrogen loading capacity and does not have any relationship with the distance to the hydrogen source. Therefore, liquid hydrogen tanker trucks are more suitable for large-scale, long-distance hydrogen transportation scenarios. Without considering subsidies, when the transportation distance is 100 km, the cost of hydrogen storage and transportation is 7.25 yuan/kg. When the transportation distance is increased to 500 km, the cost of hydrogen storage and transportation is 8.27 yuan/kg (refer to "Fig. 5.3.2.4 & Fig. 5.3.2.5 Sensitivity Calculation of Storage and Transportation Cost of Liquid Hydrogen Tanker Trucks to Distance from Hydrogen Sources").

Fig. 5.3.2.4 Sensitivity Calculation of Storage and Transportation Cost of Liquid Hydrogen Tanker Trucks to Distance from Hydrogen Source

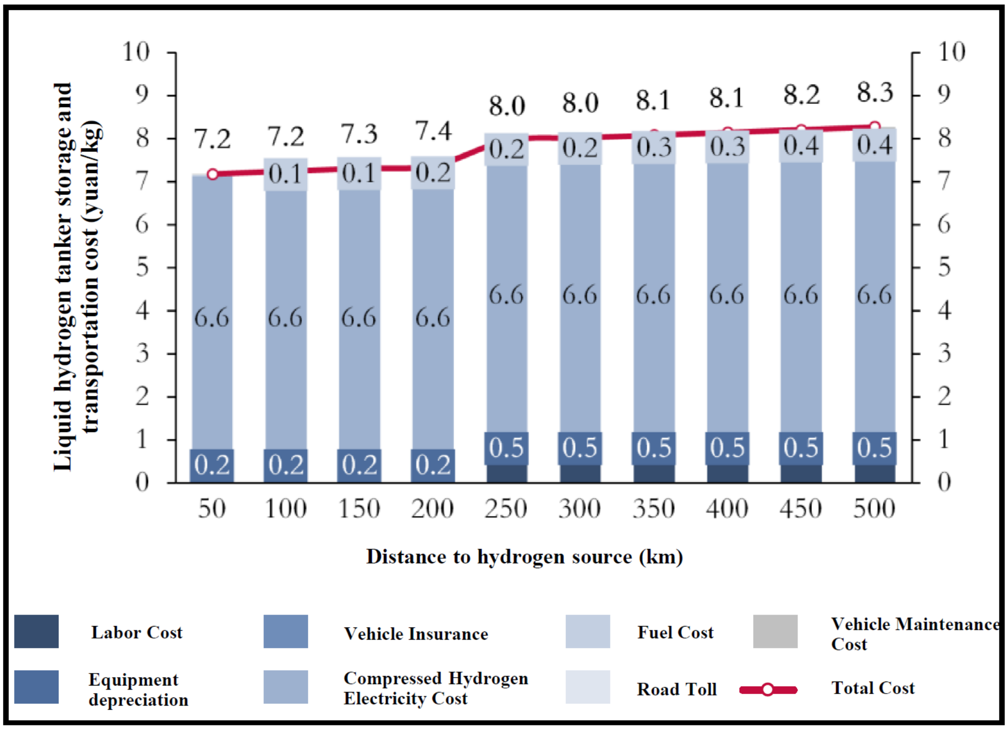


Fig. 5.3.2.5 Sensitivity Calculation of Storage and Transportation Cost of Liquid Hydrogen Tanker Trucks to Distance from Hydrogen Source

Distance to Hydrogen Source	Unit	50	100	150	200	250	300	350	400	450	500
Liquid Hydrogen Tanker Loading Capacity	**kg**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**
Daily Round Trips	**Time**	**1.0**	**1.0**	**1.0**	**1.0**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Daily Working Time	h	15	15	15	15	15	15	15	15	15	15
Length of Trailer Loading and Unloading of Hydrogen	h	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Average Trailer Speed	km/h	50	50	50	50	50	50	50	50	50	50
Number of Working Days Per Year	**Day**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**	**365**
Fixed Cost	**Yuan/kg**	**0.52**	**0.52**	**0.52**	**0.52**	**1.04**	**1.04**	**1.04**	**1.04**	**1.04**	**1.04**
Depreciation of Equipment	**Yuan/kg**	**0.24**	**0.24**	**0.24**	**0.24**	**0.48**	**0.48**	**0.48**	**0.48**	**0.48**	**0.48**
Liquid Hydrogen Tanker Price	Ten-thousand Yuan/vehicle	350	350	350	350	350	350	350	350	350	350
Years of Depreciation	Year	10	10	10	10	10	10	10	10	10	10
Labor Cost	**Yuan/kg**	**0.27**	**0.27**	**0.27**	**0.27**	**0.55**	**0.55**	**0.55**	**0.55**	**0.55**	**0.55**
Per Capita Salary	Ten-thousand Yuan /Person-Year	10	10	10	10	10	10	10	10	10	10
Number of Employees	People	4	4	4	4	4	4	4	4	4	4
Vehicle Insurance	**Yuan/kg**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Vehicle Insurance Cost	Ten-thousand Yuan/Year	1	1	1	1	1	1	1	1	1	1
Variable Cost	Yuan/kg	**6.66**	**6.73**	**6.79**	**6.85**	**6.92**	**6.98**	**7.04**	**7.11**	**7.17**	**7.23**
Fuel Cost	**Yuan/kg**	**0.04**	**0.08**	**0.12**	**0.16**	**0.20**	**0.24**	**0.28**	**0.33**	**0.37**	**0.41**
Fuel Consumption Per 100Km	L	25	25	25	25	25	25	25	25	25	25
Diesel Fuel Price	Yuan/L	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Vehicle Maintenance Cost	**Yuan/kg**	**0.01**	**0.02**	**0.02**	**0.03**	**0.04**	**0.05**	**0.05**	**0.06**	**0.07**	**0.08**
Vehicle Maintenance Cost	Yuan /km	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Road Toll	**Yuan/kg**	**0.02**	**0.03**	**0.05**	**0.06**	**0.08**	**0.09**	**0.11**	**0.12**	**0.14**	**0.15**
Road Toll	Yuan /km	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Compressed Hydrogen Electricity Cost	**Yuan/kg**	**6.60**	**6.60**	**6.60**	**6.60**	**6.60**	**6.60**	**6.60**	**6.60**	**6.60**	**6.60**
Compressed Hydrogen Electricity Consumption	kWh/kg	11	11	11	11	11	11	11	11	11	11
Electricity Price	Yuan/kWh	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total Cost	**Yuan/kg**	**7.18**	**7.25**	**7.31**	**7.37**	**7.96**	**8.02**	**8.08**	**8.15**	**8.21**	**8.27**

5.3.3 Hydrogen Refueling

Hydrogen refueling is primarily divided into on-site hydrogen production and off-site hydrogen production. Currently, hydrogen refueling stations in China primarily operate in the off-site hydrogen production mode.

1) Cost Model of Hydrogen Refueling

1.1) Key Assumptions

According to the location of hydrogen preparation, hydrogen refueling stations can be divided into on-site hydrogen refueling stations and off-site hydrogen refueling stations. At present, hydrogen refueling stations in China primarily produce hydrogen off-site. This means that hydrogen is stored and transported to the refueling station, where it is then compressed, stored, and used for refueling purposes. Given that the operating cost of a hydrogen refueling station is strongly correlated with the capacity utilization rate of the refueling unit, this model uses an example of a refueling station with a refueling pressure of 35 MPa and a daily refueling capacity of 500 kg, and analyzes the operating cost of the hydrogen refueling station by varying the capacity utilization rate of the station. To comprehensively evaluate the economics of hydrogen refueling, this model currently does not incorporate the subsidy factor. However, it may be utilized as a policy regulator to guide cost-reduction efforts in subsequent discussions. The key assumptions of the model for the current time node are outlined below:

1) Annual Hydrogen Refueling Capacity: The hydrogen refueling station utilizes a 35 MPa hydrogen refueling device with a daily hydrogen refueling capacity of 500 kg/day and operates 300 days per year.

2）Hydrogen Price: The retail price of hydrogen is 20 yuan/kg.

3）Storage and Transportation Cost: The hydrogen refueling station is responsible for storage. Presently, short-distance transportation is primarily conducted via 20 MPa tube trailers, with a cost of 7.79 yuan/kg (refer to section 5.3.2 Hydrogen Storage and Transportation for details).

4）Refueling Cost:

- Depreciation Cost: The construction cost is 12 million yuan, depreciated over 15 years. The land cost is 3 million yuan, depreciated over 30 years.
- Labor Cost: The per capita salary is 80,000 yuan per person-year, with each hydrogen refueling station being equipped with 5 staff members.
- Operation and Maintenance Cost: The operation and maintenance costs amount to 400,000 yuan per year.

1.2) Data Analysis

According to the model's measurements, without considering subsidies, when the capacity utilization rate is 20%, the operating cost of the hydrogen refueling station amounts to 84.45 yuan/kg. When the capacity utilization rate of the hydrogen refueling station is increased to 100%, the operating cost decreases to 39.12 yuan/kg. However, it still lacks the competitiveness required for large-scale promotion. Therefore, the core factor for the application of hydrogen fuel cell vehicles lies in further reducing the operating cost of hydrogen refueling stations (refer to "Fig. 5.3.3.1 Sensitivity Calculation of Hydrogen Refueling Station Operating Cost to Gross Profit Margin").

Fig. 5.3.3.1 Sensitivity Calculation of Hydrogen Refueling Station Operating Cost to Gross Profit Margin

Capacity Utilization	Unit	20%	40%	60%	80%	100%
Hydrogen Source Price	Yuan/kg	20.00	20.00	20.00	20.00	20.00
Storage and Transportation Cost	Yuan/kg	7.79	7.79	7.79	7.79	7.79
Refueling Cost	Yuan/kg	56.67	28.33	18.89	14.17	11.33
Annual Hydrogen Refueling Volume (35mpa)	kg/year	30,000	60,000	90,000	120,000	150,000
Daily Hydrogen Refueling Volume (35mpa)	kg/day	500	500	500	500	500
Annual Operating Days	Day	300	300	300	300	300
Depreciation Cost	Yuan/kg	30.00	15.00	10.00	7.50	6.00
Construction Cost	Ten thousand yuan	1,200	1,200	1,200	1,200	1,200
Years of Depreciation	Year	15	15	15	15	15
Land Cost	Ten thousand yuan	300	300	300	300	300
Years of Depreciation	Year	30	30	30	30	30
Labor Cost	Yuan/kg	13.33	6.67	4.44	3.33	2.67
Per Capita Salary	Ten-thousand Yuan /Person-Year	8	8	8	8	8
Number of Employees	People	5	5	5	5	5
Operation And Maintenance Cost	Yuan/kg	13.33	6.67	4.44	3.33	2.67
Operation and Maintenance Cost	Ten-thousand Yuan/Year	40	40	40	40	40
Total Cost	Yuan/kg	84.45	56.12	46.67	41.95	39.12

2) Cost Reduction Model of Hydrogen Refueling

2.1) Key Assumptions

In addition to capacity utilization rate, there are other key factors in minimizing the operating costs of these refueling stations: the pricing of hydrogen sources, the expenses related to hydrogen storage and transportation, and the construction costs of hydrogen refueling stations. The key assumptions of the hydrogen cost-reduction model are as follows:

1) Hydrogen Price: The price stands at 20 yuan/kg. Looking ahead, as large-scale hydrogen production and electrolysis technology mature gradually, the model anticipates that the average annual decrease in the cost of hydrogen sources will be 10% from 2022 to 2025, and 5% from 2025 to 2030 (refer to section 5.3.1 Hydrogen Production and "Fig. 5.1.1.4 Annualized Cost Reduction Assumptions for Hydrogen Fuel Cell Vehicles and the Hydrogen Industry Supply Chain").

2）Storage and Transportation Cost: At present, 20 MPa tube trailers are primarily utilized for short-distance storage and transportation at a cost of 7.79 yuan/kg. Looking ahead, as pipeline storage and transportation technology matures, the model assumes an average annualized reduction of storage and transportation costs by 10% over the period from 2022 to 2030 (refer to section 5.3.2 Hydrogen Storage and Transportation and "Fig. 5.1.1.4 Annualized Cost Reduction Assumptions for Hydrogen Fuel Cell Vehicles and Hydrogen Industry Supply Chain").

3）Construction Cost: The current construction cost for a single hydrogen refueling station stands at 12 million yuan, with the core equipment mainly imported, including compressors, hydrogen refueling guns and hoses, flow meters, safety valves, hydrogen pipelines, and valves. Looking ahead, there will be cost reductions as hydrogen refueling stations are built on a larger scale or combined with other types of refueling stations (a combination of gasoline/hydrogen/natural gas refueling), core facilities are advanced, and more domestically produced equipment are used. The model projects the construction cost to decrease by 20% annually during this period and by 10% annually from 2025 to 2030 (refer to "Fig. 5.1.1.4 Annualized Cost Reduction Assumptions for Hydrogen Fuel Cell Vehicles and Hydrogen Industry Supply Chain").

4）Capacity Utilization Rate: The current hydrogen refueling stations operate at a capacity utilization rate of 60%. As hydrogen fuel cell vehicles become more widespread in the future, this rate is expected to steadily rise. The model predicts an average annual increase of 5% in the capacity utilization rate of hydrogen refueling stations from 2022 to 2030, reaching full capacity (100%) by 2030.

2.2) Data Analysis

According to the model's measurements, the current operating cost of a hydrogen refueling station stands at 46.67 yuan per kilogram. By 2030, this cost is projected to decrease to 22.25 yuan per kilogram, which falls below the target price of hydrogen refueling set at 25 yuan per kilogram. This reduction in operating costs ensures that hydrogen fuel cell vehicles can initially compete economically with conventional fuel vehicles and pure electric vehicles in terms of fuel costs (refer to "Fig. 5.3.3.2 Operating Cost Reduction Calculation of Hydrogen Refueling Station ").

Fig. 5.3.3.2 Cost Reduction Calculation of Hydrogen Refueling Station Operating Cost

Items	Unit	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydrogen Source Price	**Yuan/kg**	**20.00**	**18.00**	**16.20**	**14.58**	**13.85**	**13.16**	**12.50**	**11.88**	**11.28**
Average Annual Reduction	*%*		*10%*	*10%*	*10%*	*5%*	*5%*	*5%*	*5%*	*5%*
Storage and Transportation Cost	**Yuan/kg**	**7.79**	**7.01**	**6.31**	**5.68**	**5.11**	**4.60**	**4.14**	**3.72**	**3.35**
Average Annual Reduction	*%*		*10%*	*10%*	*10%*	*10%*	*10%*	*10%*	*10%*	*10%*
Refueling Cost	**Yuan/kg**	**18.89**	**15.79**	**13.45**	**11.64**	**10.57**	**9.66**	**8.88**	**8.20**	**7.61**
Annual Hydrogen Refueling Volume (35MPa)	**kg/year**	**90,000**	**97,500**	**105,000**	**112,500**	**120,000**	**127,500**	**135,000**	**142,500**	**150,000**
Daily Hydrogen Refueling Volume (35MPa)	kg/day	500	500	500	500	500	500	500	500	500
Annual operating days	Day	300	300	300	300	300	300	300	300	300
Capacity Utilization	%	60%	65%	70%	75%	80%	85%	90%	95%	100%
Average Annual Growth	*%*		*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
Depreciation cost	**Yuan/kg**	**10.00**	**7.59**	**5.83**	**4.53**	**3.91**	**3.39**	**2.95**	**2.59**	**2.28**
Construction cost	Ten thousand yuan	1,200	960	768	614	553	498	448	403	363
Average Annual Reduction	*%*		*20%*	*20%*	*20%*	*10%*	*10%*	*10%*	*10%*	*10%*
Years of Depreciation	Year	15	15	15	15	15	15	15	15	15
Land Cost	Ten thousand yuan	300	300	300	300	300	300	300	300	300
Years of Depreciation	Year	30	30	30	30	30	30	30	30	30
Labor Cost	**Yuan/kg**	**4.44**	**4.10**	**3.81**	**3.56**	**3.33**	**3.14**	**2.96**	**2.81**	**2.67**
Per Capita Salary	Ten-thousand Yuan /Person-Year	8	8	8	8	8	8	8	8	8
Number of Employees	People	5	5	5	5	5	5	5	5	5
Operation and Maintenance Cost	**Yuan/kg**	**4.44**	**4.10**	**3.81**	**3.56**	**3.33**	**3.14**	**2.96**	**2.81**	**2.67**
Operation and Maintenance Cost	Ten-thousand Yuan/Year	40	40	40	40	40	40	40	40	40
Total Cost	**Yuan/kg**	**46.67**	**40.80**	**35.95**	**31.90**	**29.53**	**27.42**	**25.52**	**23.80**	**22.25**

5.4 Cost Reduction Calculations Based on Cost Learning Curve

1) Analysis of Hydrogen Cost Model and Cost Reduction Model

1.1) Key Assumptions

The Hydrogen Council has highlighted that widespread deployment of hydrogen-energy projects and the expansion of hydrogen-energy-related industrial chains will lead to a significant reduction in the total cost of ownership (TCO) associated with hydrogen.[19] Historical data indicates that the cost of green hydrogen has decreased by 60% over a decade, falling from approximately US$10-15/kg in 2010 to around US$4-6/kg by 2020.[35] In the realm of renewable energy, we often use a learning curve to illustrate the correlation between scale and cost.[36] The analysis method utilizing learning curves has found widespread application in predicting future costs for wind power and photovoltaics [37] . At the heart of the learning curve lies the learning rate, defined as the percentage decrease in unit production cost when the production scale doubles. The learning-rate-based cost curve can be described by the following equation:

$$\boldsymbol{C_t = C_0 \times (1 - learningrate)^{log_2 \frac{I_t}{I_0}}}$$

Where C_t and C_0 represent the cost at moment t and the initial moment, respectively, and I_t and I_0 denote the cumulative yield at moment t and the initial moment, respectively.

1.2) Data Analysis

According to data published by the National Energy Administration (NEA), the learning rate stands at 14% for photovoltaics (PV) and 7% for wind power. As a significant factor contributing to the cost of hydrogen production, electrolyzers exhibit a learning rate of 18%.[38] The primary reason for the relatively low learning rate of wind power is attributed to the high transportation and installation costs associated with wind turbines, which are challenging to reduce through scale alone. Therefore, the learning rate for hydrogen costs is projected to be 7% under a conservative forecast, 10% under a medium-range forecast, and 14% under an optimistic forecast.

According to forecasts from the China Hydrogen Energy Alliance, China's cumulative shipments of hydrogen production equipment are projected to exceed 70 GW by 2030[39, 40].This growth represents a doubling of shipments six times over the cumulative shipments recorded in 2022. According to the model's measurements, with the current hydrogen price at 35 yuan/kg and assuming the profit margin remains constant, the conservative forecast for the hydrogen price in 2030 is projected to be 23 yuan/kg, the medium-range forecast at 19 yuan/kg, and the optimistic forecast at 14 yuan/kg (refer to "Fig. 5.3.4.1 Cost Reduction Calculation of Hydrogen Price"). The forecast results are largely aligned with the cost reduction analysis of the various segments within the hydrogen industry supply chain (refer to "Fig. 5.3.3.2 Cost Reduction Calculation of Hydrogen Refueling Station Operating Cost"). Furthermore, the terminal cost of hydrogen is anticipated to reach 22.25 yuan/kg by 2030.

Fig. 5.3.4.1 Cost Reduction Calculation of Hydrogen Price

Assumption	Unit	Conservative	Neutral	Optimistic
Learning Rate of Hydrogen Cost	%	7%	10%	14%
Hydrogen Production Price in 2030	Yuan/kg	23	19	14

2) Analysis of Hydrogen Fuel Cell Vehicle Cost Model and Cost Reduction Model

Likewise, the author utilized the terminal sales growth of hydrogen vehicles to estimate the reduction rate of terminal costs for hydrogen vehicles. According to the Medium- and Long-term Plan for the Development of the Hydrogen Energy Industry (2021-2035) released by the National Development and Reform Commission and the National Energy Administration, China's hydrogen fuel cell vehicle fleet is projected to reach 50,000 by 2025 and 200,000 by 2030 under conservative estimates. Based on historical data indicating that the number of hydrogen fuel cell vehicles in China in 2022 is 12,682 and with a learning rate of 18%,[41] it is estimated that the selling price of hydrogen fuel cell vehicles in China will decrease to 67.5% of the 2022 price by 2025 and further decline to 45.4% of the 2022 price by 2030, assuming profit margins remain constant. This prediction aligns closely with the cost reduction analysis forecast for hydrogen fuel cell vehicles (refer to 5.1 Operating Cost and Cost Reduction Model Analysis of Vehicles for more details).

$$\frac{\boldsymbol{Thepriceoffuelcellvehicles\ in\ China\ in\ 2025}}{\boldsymbol{Thepriceoffuelcellvehicles \in China \in 2022}} = \ast 1 - 18\% +^{log_2\left(\frac{50000}{12682}\right)} = 67.5\%$$

$$\frac{\boldsymbol{Thepriceoffuelcellvehicles\ in\ China\ in\ 2030}}{\boldsymbol{Thepriceoffuelcellvehicles\ in\ China\ in\ 2022}} = \ast 1 - 18\% +^{log_2\left(\frac{200000}{12682}\right)} = 45.4\%$$

5.5 ESG Cost and Cost Reduction Model Analysis

ESG (Environmental, Social, and Governance) costs play a crucial role in determining vehicle economics. Vehicles following various technology paths (conventional fuel, hydrogen fuel cell, and pure electric) exhibit varying life-cycle carbon emissions.[42] New-energy vehicles, including hydrogen fuel cell vehicles and pure electric vehicles, boast substantially lower final life-cycle carbon emissions compared to conventional fuel vehicles. This reduction primarily stems from the lower carbon emissions during the fuel production process of new-energy vehicles and the absence of carbon emissions during their fuel usage phase.

According to the Ecoinvent 3.5 database, the carbon emission factors per kilowatt-hour (kWh) for various power sources are approximately as follows: thermal power: 1.0633 kg CO_2/kWh; hydropower: 0.0044 kg CO_2/kWh; solar power: 0.0897 kg CO_2/kWh; wind power: 0.0214 kg CO_2/kWh; and nuclear power: 0.0138 kg CO_2/kWh. According to the National Energy Administration's 22 National Electric Power Industry Statistics, as of the end of December 2022, the country's installed power generation capacity was 2,564,050,000 kW. Thermal power constituted 51.96% of this capacity, hydropower 16.13%, solar power 15.31%, wind power 14.25%, and nuclear power 2.17%. Therefore, the average carbon emission factor of China's power grid can be calculated as 0.565 $kg_{CO2/kWh}$. In the future, as we transition towards a greener grid, the share of thermal power is projected to decrease to below 25%. Moreover, it's anticipated that the average carbon emission factor of China's power grid will plummet to just 0.3 kg CO_2/kWh.[42]

Given the current efficiency of hydrogen production, the efficiency of converting hydrogen to electricity stands at approximately 55kWh/kg H_2. According to the China Hydrogen Industry Development Report 2020, the carbon emissions associated with producing hydrogen is 13.9 kg CO_2/kg H_2. In the future, advancements in hydrogen production efficiency, coupled with a greater proportion of hydrogen derived from renewable energy sources, are poised to significantly slash the carbon emissions associated with hydrogen production, potentially bringing it down to 6.5kg CO_2/kg H_2.[42]

Based on the provided carbon emission factors of China's power grid and hydrogen, along with other key parameters, it can be calculated that the current carbon emissions of conventional fuel vehicles throughout their entire life cycle amount to 41.6 tons. This figure is expected to decrease to 32.0 tons by 2035 (refer to "Fig. 5.5.1 Calculation of Life Cycle Carbon Emissions of Conventional Fuel Vehicles"). Meanwhile, the carbon emissions of hydrogen fuel cell vehicles are currently calculated at 41.0 tons, with an anticipated reduction to 16.2 tons by 2035 (refer to "Fig. 5.5.2 Calculation of Life Cycle Carbon Emissions of Hydrogen Fuel Cell Vehicles"). Conversely, the carbon emissions from pure electric vehicles are currently estimated at 22.6 tons, projected to decline to 10.0 tons by 2035 (refer to "Fig. 5.5.3 Calculation of Life Cycle Carbon Emissions of Pure Electric Vehicles"). Currently, the carbon emissions of hydrogen fuel cell vehicles are elevated due to the utilization of gray hydrogen. However, as the shift from gray hydrogen to blue and green hydrogen production methods progresses, the carbon emissions generated during the hydrogen production process are anticipated to decline significantly.[42]

Fig. 5.5.1 Calculation of Life Cycle Carbon Emissions of Conventional Fuel Vehicles

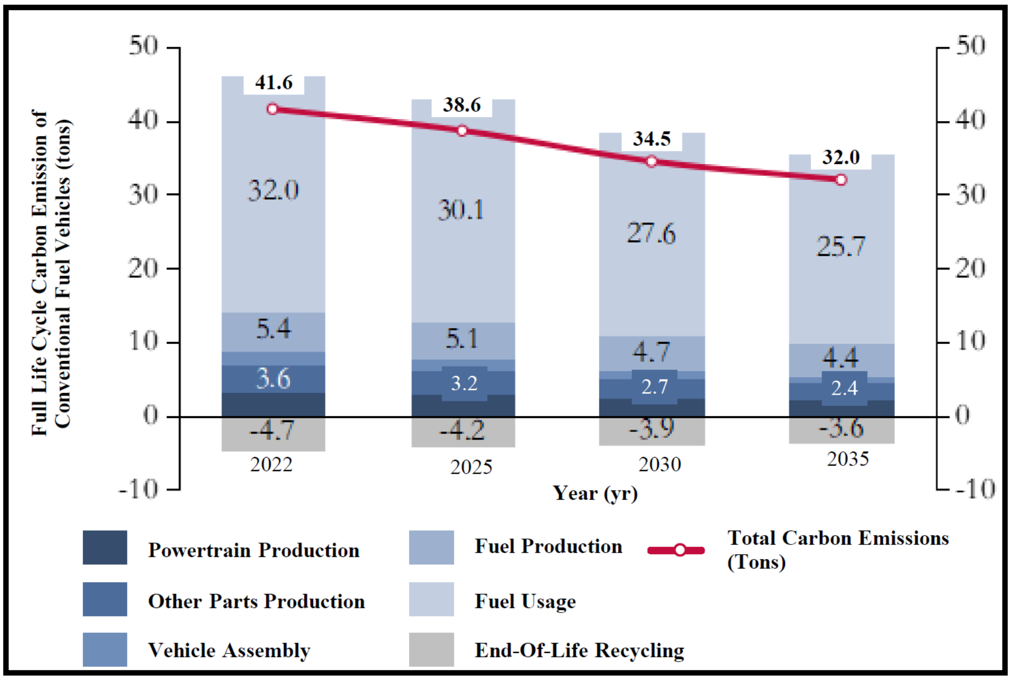


Fig. 5.5.2 Calculation of Life Cycle Carbon Emissions of Hydrogen Fuel Cell Vehicles

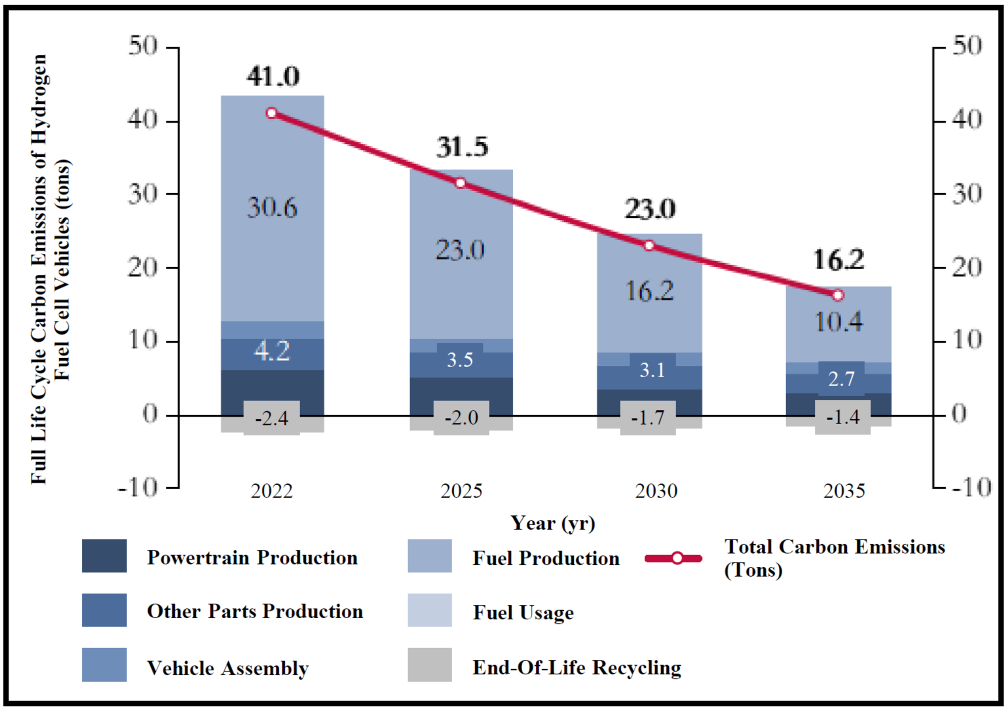
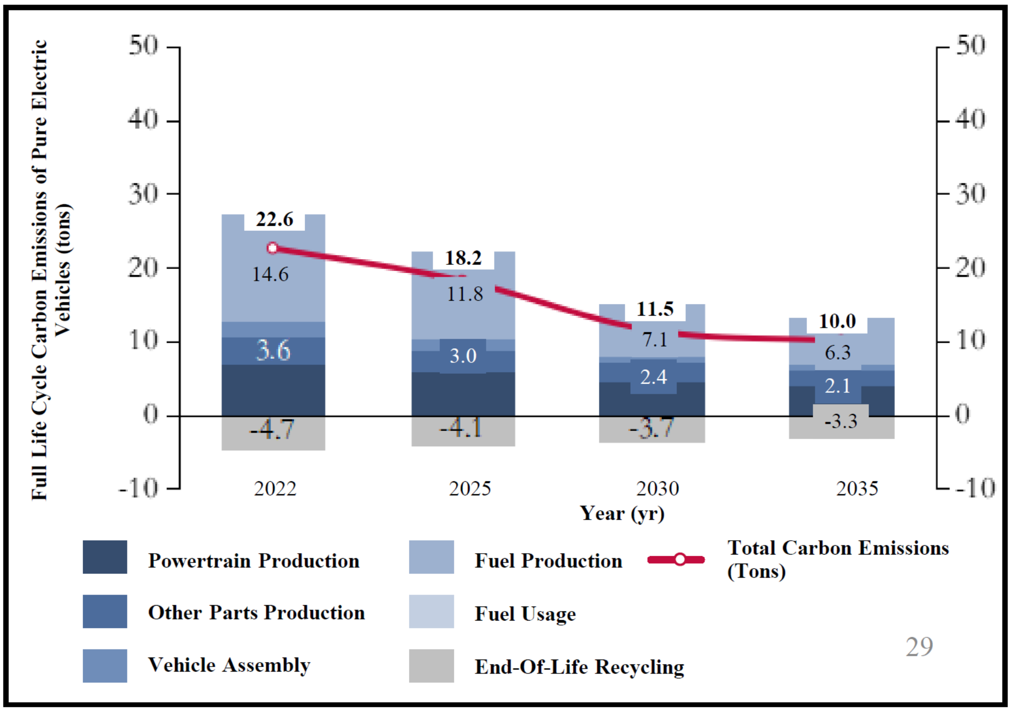


Fig. 5.5.3 Calculation of Life Cycle Carbon Emissions of Pure Electric Vehicles



According to the current carbon tax price of 55 yuan/ton of CO2 in the domestic carbon market, the current carbon tax for conventional fuel vehicles amounts to 2,288 yuan, which is expected to decrease to 1,760 yuan by 2035. Meanwhile, the current carbon tax for hydrogen fuel cell vehicles stands at 2,255 yuan, projected to reduce to 891 yuan by 2035. Finally, the current carbon tax for pure electric vehicles is 1,243 yuan, anticipated to decline to 550 yuan by 2035. As the carbon tax price escalates in the future, it is anticipated that the disparity between the carbon tax imposed on new-energy vehicles and that levied on conventional fuel vehicles will widen even further (see "Fig. 5.5.4 Comparison of Calculation of Life Cycle Carbon Emissions of Automobiles").

Furthermore, the cost of Carbon Capture, Utilization, and Storage (CCUS) technology will play a crucial role in influencing the operating costs of vehicles across various technical strategies, including conventional fuel, hydrogen fuel cell, and pure electric vehicles. At present, China's Carbon Capture, Utilization, and Storage (CCUS) technology is in its early stages, with the full process cost ranging from 350 to 900 yuan/ton of CO2. It is projected that by 2035, this cost will decrease to 250-650 yuan/ton of CO2. Capital investment and energy consumption during the capture process are identified as the primary contributors to these costs.[43, 44] According to the model's calculations for the full life-cycle carbon emissions of vehicles, the current Carbon Capture, Utilization, and Storage (CCUS) cost for conventional fuel vehicles ranges from 15,000 to 37,000 yuan. This cost is expected to decrease to 8,000-21,000 yuan by 2035. Similarly, the current carbon tax on hydrogen fuel cell vehicles is estimated at 14,000-37,000 yuan, projected to decrease to 0.4-11,000 yuan by 2035. For conventional fuel vehicles, the current carbon tax ranges from 0.8-20,000 yuan and is anticipated to decrease to 0.3-0.7 million yuan by 2035 (refer to "Fig. 5.5.5 Comparison of the Calculation of the Whole-Process Cost of CCUS for the Full Life Cycle of Vehicle").

Fig. 5.5.4 Comparison of Carbon Emission Calculation for the Full Life Cycle of Vehicle

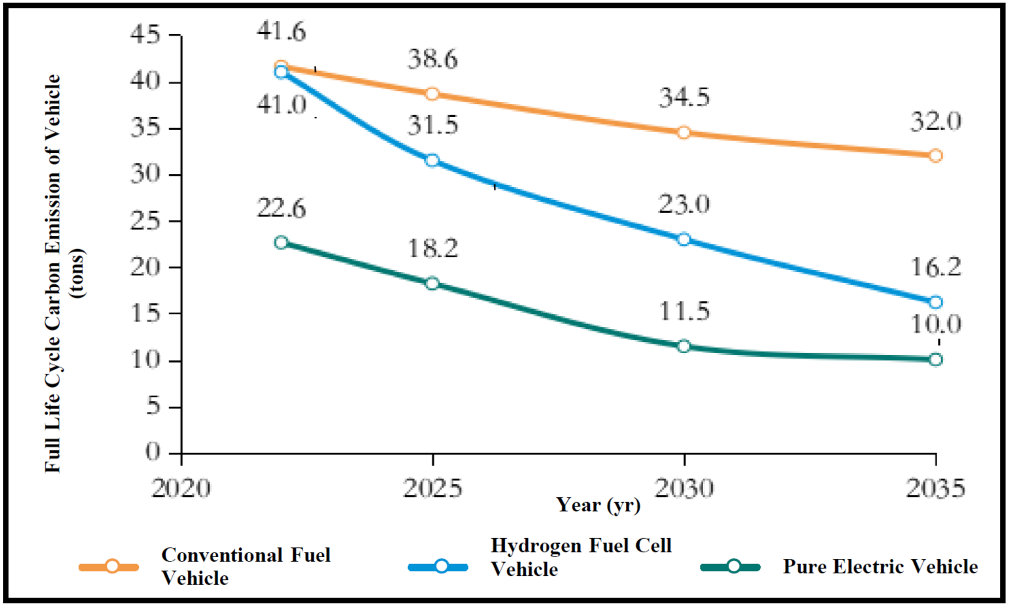


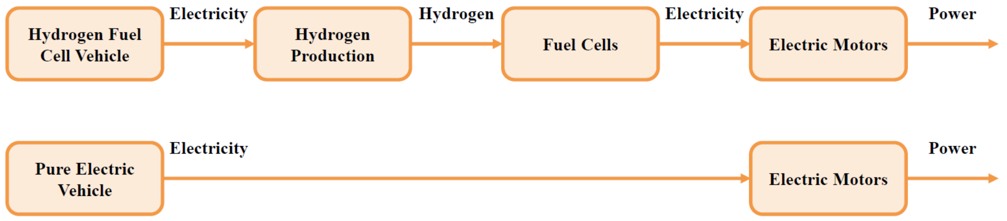
Fig. 5.5.5 Comparison of the Calculation of the Whole-Process Cost of CCUS for the Full Life Cycle of Vehicle

	Carbon Emissions (tons)		CCUS full process cost (ten thousand yuan)	
	2022	2035	2022	2035
Conventional Fuel Vehicle	41.6	32.0	1.5 - 3.7	0.8 - 2.1
Hydrogen Fueled Vehicle	41.0	16.2	1.4 - 3.7	0.4 - 1.1
Pure Electric Vehicle	22.6	10.0	0.8 - 2.0	0.3 - 0.7

CHAPTER 6 APPLICATION CASE ANALYSIS

According to public information and research conducted by A.T. Kearney, it is anticipated that the primary source of hydrogen energy in the future will be derived from electrolysis of water. However, it's noted that there is an efficiency loss in the process of "hydrogen production by electrolysis of water and electricity generation by fuel cells." This inefficiency results in the economic viability of hydrogen fuel cells being inferior to that of lithium-ion batteries under comparable circumstances (refer to "Fig. 6.1 Schematic Illustration of Energy Efficiency of Hydrogen Fuel Cell Vehicles and Pure Electric Vehicles"). Despite the efficiency limitations mentioned, lithium-ion batteries face constraints due to their energy densities by weight and by volume. This restricts the number of batteries and weight they can carry, rendering them unsuitable for certain specific scenarios. They are more apt for transportation scenarios characterized by "short-distance and light-loading." On the other hand, the energy density of hydrogen fuel cells and hydrogen storage systems far exceeds that of lithium-ion batteries. This makes them better suited for transportation scenarios involving "long-distance and heavy-loading" as depicted in "Fig. 6.2 Application Scenario Breakdown of New Energy Heavy-duty Trucks."

Fig. 6.1 Schematic Illustration of Energy Efficiency of Hydrogen Fuel Cell Vehicles and Pure Electric Vehicles



	Hydrogen Production Efficiency	Fuel Cell Power Generation Efficiency	Motor Efficiency	Total efficiency
Hydrogen Fueled Vehicle	75%	60%	95%	43%
Pure Electric Vehicle	-	-	95%	95%

Fig. 6.2 Application Scenario Breakdown of New Energy Heavy-duty Trucks

Vehicle Type	Application Scenario	Market share	Scope of application			Pure Electric Heavy Truck Penetration Potential	Hydrogen Fueled Heavy Duty Truck Penetration Potential
			Distance (km)	Load (tons)	Applicable Industries		
Tractor Trailers	Mainline Transportation	8%	>1000	43/49	Logistics	Low	Medium
	Long-distance Transportation	17%	>1000	43/49	Logistics	Low	Medium
	Medium and Long Distance Transportation	11%	500-1000	43/49	Coal transportation	Low	High
	District and City Transportation	6%	200-500	43/49	Coal transportation	Medium	High
Dump trucks	Long-distance Transportation	12%	>500	≤31	Industrial	Low	Medium
	Medium and Long Distance Transportation	10%	300-500	≤25	Industrial	Medium	High
	District and City Transportation	3%	200-400	≤25	Construction	Medium	High
Trucks	Road Freight Heavy Transportation	4%	20-200	55-65	Coal, Steel, Construction, Mining	Medium	High
	Construction Site Heavy Transportation	6%	20-200	60-100	Coal, Steel, Construction, Mining	Low	High
	Construction Site Standard Load Transportation	6%	10-100	31-55	-	High	Medium
	Road Freight Standard Load Transportation	7%	10-50	25-55	-	High	Medium
Specialized Vehicles	Heavy-duty Sanitation and Cleaning Operations	2%	≤50	25-40	Sanitation Company	High	Medium
	Heavy Dangerous Goods Transportation	1%	100-500	25-32	Energy, Chemicals	Medium	Medium
	Heavy Construction	7%	20-200	31-35	Construction	High	Medium
	Heavy Duty Specialty Work	1%	10-200	25-80	Energy, Construction	Medium	Medium

Based on theoretical model results presented in this thesis, the author infers that, when solely considering the economic dimension, hydrogen fuel cell heavy-duty trucks, particularly in scenarios characterized by "cheap hydrogen sources + concentrated hydrogen demand" (such as coal, steel, and coking parks in provinces like Shanxi, Shaanxi, and Hebei, where inexpensive industrial by-product hydrogen is used extensively within the same park, reducing transportation costs), could see hydrogen prices fall below 20 yuan/kg. Additionally, hydrogen fuel cell logistics vehicles operating in specific segments like fresh food and cold-chain logistics are expected to be the earliest adopters of hydrogen technology based on economic considerations. In Northwest China, leveraging local abundant renewable resources can enable the implementation of on-site hydrogen production through water electrolysis within the same park. This strategy can further drive down the cost of hydrogen and facilitate the transition from gray hydrogen to green hydrogen. In the following sections, we will present practical application cases corresponding to each of the aforementioned scenarios, demonstrating how they validate the modeling results presented in this thesis.

6.1 Jinnan Iron and Steel Case: “Cheap Industrial By-production Hydrogen + Centralized Hydrogen Demand in the Park”

According to the "Shenneng China Hydrogen Industry Development White Paper," Shanxi Jinnan Iron and Steel Group Co., Ltd. is a major iron and steel enterprise, listed among the "Top 500 Chinese Enterprises" and the "Top 20 Domestic Iron and Steel Enterprises." The company covers an area of about 18,000 acres, with a total investment of approximately 20 billion yuan and a workforce of about 6,000 employees. In 2022, the company's revenue is projected to surpass 50 billion yuan, supported by an annual production capacity of 8 million tons of iron, 10 million tons of steel, 10 million tons of steel products, 3.15 million tons of coke, and 450,000 tons of chemicals.

Additionally, it has established an integrated industrial model encompassing "steel - coke - chemicals - hydrogen energy." This is illustrated in Fig. 6.1.1 Shanxi Jinnan Iron and Steel Coking Plant" and "Fig. 6.1.2 Shanxi Jinnan Iron and Steel Chemical Park.

The company currently operates nearly 200 hydrogen fuel cell heavy-duty trucks and electric heavy-duty trucks. Among these, the hydrogen fuel cell heavy-duty trucks utilize "cheap by-product hydrogen resources" and "centralized hydrogen demand". Combined with refined logistics operations, the company achieves the efficiency of hydrogen logistics (refer to "Fig. 6.1.3 Shanxi Jinnan Iron and Steel Hydrogen fuel cell Heavy-duty trucks" and "Fig. 6.1.4 Shanxi Jinnan Iron and Steel Hydrogen Refueling Station").

Fig. 6.1.1 Shanxi Jinnan Iron and Steel Coking Plant

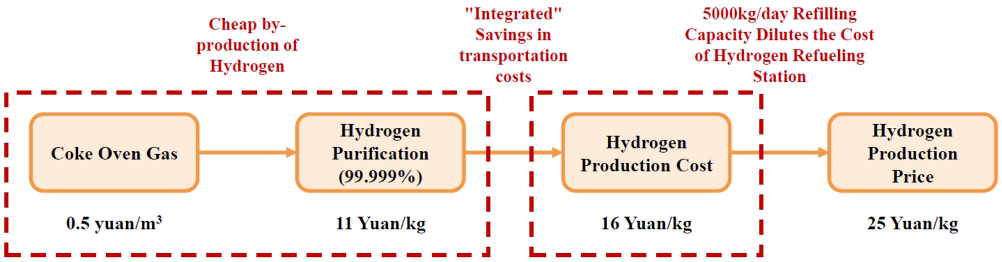
Fig. 6.1.2 Shanxi Jinnan Iron and Steel Chemical Park

Fig. 6.1.3 Shanxi Jinnan Iron & Steel Hydrogen Fuel Cell Heavy-duty Trucks

Fig. 6.1.4 Shanxi Jinnan Iron and Steel Hydrogen Fueling Station

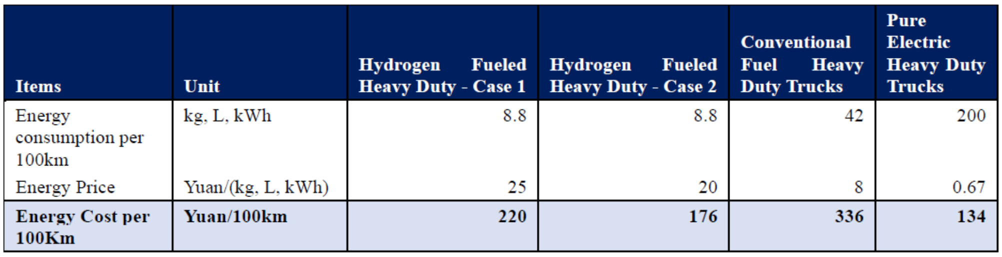
On the hydrogen consumption side, the company has high-intensity demand, utilizing hydrogen fuel cell heavy-duty trucks for 24-hour transportation of materials. On the hydrogen production side, the company benefits from cheap by-product hydrogen resources, with the current annual output reaching 600 million cubic meters. Approximately 60-70% of this hydrogen is utilized in the chemical industry, 18,000 tons are used in blast furnace smelting, and the remainder undergoes further purification to achieve a purity level of 99.999%. This purified hydrogen is then used in hydrogen fuel cell heavy-duty trucks to enable clean transportation. First of all, the company produces coke oven gas from coking by-products at a remarkably low cost of only 0.5 yuan/m^3. Subsequently, through purification processes, they obtain high-purity hydrogen at an affordable production cost totaling 11.2 yuan/kg. Secondly, the company mitigates hydrogen transportation costs by implementing on-site "integrated" storage and transportation solutions. This strategy reduces the cost of hydrogen production and delivery to 16 yuan/kg. Finally, by combining the company's significant hydrogen demand with the establishment of on-site hydrogen refueling stations, the company achieves a substantial refueling volume of 5,000 kg/day. This volume helps to amortize the costs associated with hydrogen refueling stations. Alongside generating a certain profit from these refueling stations, this approach results in a hydrogen price that is lower than 25 yuan/kg (refer to "Fig. 6.1.5 Shanxi Jinnan Iron and Steel Hydrogen Industry Supply Chain" for details).

Fig. 6.1.5 Shanxi Jinnan Iron and Steel Hydrogen Industry Supply Chain



According to the company's analysis, the hydrogen consumption for their hydrogen fuel cell heavy-duty trucks is 8.8 kg per 100 km, with hydrogen prices varying between 25 yuan/kg and 20 yuan/kg. In comparison, conventional fuel heavy-duty trucks consume 42 liters of fuel per 100 km, with fuel prices at 8 yuan per liter. Meanwhile, pure electric heavy-duty trucks consume 200 kWh of electricity per 100 km, with electricity priced at 0.67 yuan per kWh. In developing a comparative model, Jinnan Iron and Steel's hydrogen fuel cell heavy-duty trucks are found to be more cost-effective than conventional fuel heavy-duty trucks. Even if the price of producing hydrogen drops to 20 yuan/kg, hydrogen refueling stations can still maintain a certain profit margin (refer to "Fig. 6.1.6 Comparison of 100-kilometer Energy Costs for Shanxi Jinnan Iron and Steel Heavy-duty trucks" for details).

Fig. 6.1.6 Comparison of 100-kilometer Energy Costs for Shanxi Jinnan Iron and Steel Heavy-duty Trucks



Items	Unit	Hydrogen Fueled Heavy Duty - Case 1	Hydrogen Fueled Heavy Duty - Case 2	Conventional Fuel Heavy Duty Trucks	Pure Electric Heavy Duty Trucks
Energy consumption per 100km	kg, L, kWh	8.8	8.8	42	200
Energy Price	Yuan/(kg, L, kWh)	25	20	8	0.67
Energy Cost per 100Km	**Yuan/100km**	**220**	**176**	**336**	**134**

Hydrogen fuel cell heavy-duty trucks have undergone successful testing at Jinnan Iron and Steel, benefiting from industrial by-product hydrogen that serves as a cost-effective source. This, coupled with the demand for centralized heavy-duty freight transport, makes hydrogen fuel cell heavy-duty trucks economically viable at the company. The author concludes that in the transition from gray hydrogen to green hydrogen in the future, regions characterized by high-quality wind and solar resources and concentrated hydrogen demand will possess a cost advantage, enabling them to prioritize the deployment of hydrogen fuel cell heavy-duty trucks.

6.2 GLP Case: “Demand for Cold-chain logistics Vehicles with Long Distance and High Energy Consumption”

According to the "14th Five-Year Plan for Cold-chain logistics Development" issued by the State Council, there is a need to expedite the phase-out of high-emission cold chain vehicles and promote the adoption of new-energy vehicles. Therefore, new energy has become an inevitable trend in China's cold-chain logistics transportation.

According to the research report by IDG and the "Shanghai Shenneng Energy China Hydrogen Industry Development White Paper", GLP is a prominent warehousing and logistics company with a global presence, serving more than 2,400 customers. Its clientele primarily consists of leading companies in logistics, manufacturing, fast-moving consumer goods (FMCG), and retail sectors worldwide. The Group boasts the largest logistics park portfolio in China, with investments in and management of over 500 logistics parks across 70 regions nationwide, including more than 110 parks situated in the Yangtze River Delta region. The company's customers in China include major brands such as Jingdong, Walmart, Meituan, Pinduoduo, Shunfeng, McDonald's, KFC, and others. These mid- to high-end-consumer customers generate substantial orders and possess significant cold storage resources, resulting in a robust demand for cold-chain logistics and distribution services. The company has initiated pilot operations with several hydrogen fuel cell cold chain vehicles and is actively collaborating with Shanghai Shenneng Energy Development to explore application scenarios for these vehicles (refer to "Fig. 6.2.1 GLP Logistics Park", "Fig. 6.2.2 GLP Warehousing Facilities, and Fig. 6.2.3 GLP 4.5-ton Hydrogen Fuel Cell Cold Chain Vehicles").

Fig. 6.2.1 GLP Logistics Parks

Fig. 6.2.2 GLP Warehousing Facilities

Fig. 6.2.3 GLP 4.5-ton Hydrogen Fuel Cell Cold Chain Vehicles

1) Operating Cost Model

1.1) Key Assumptions

Based on feedback from interviews with cold chain operation enterprises, it has been observed that cold chain vehicles operate over long distances and consume significant amounts of electricity. Pure electric cold chain vehicles face serious range anxiety issues, only meeting daily travel needs of around 150 kilometers in southern regions, and even shorter distances in northern regions. This limited range cannot support the long-distance demands of cold-chain logistics vehicles, making pure electric cold chain vehicles unsuitable for comparison in this context.

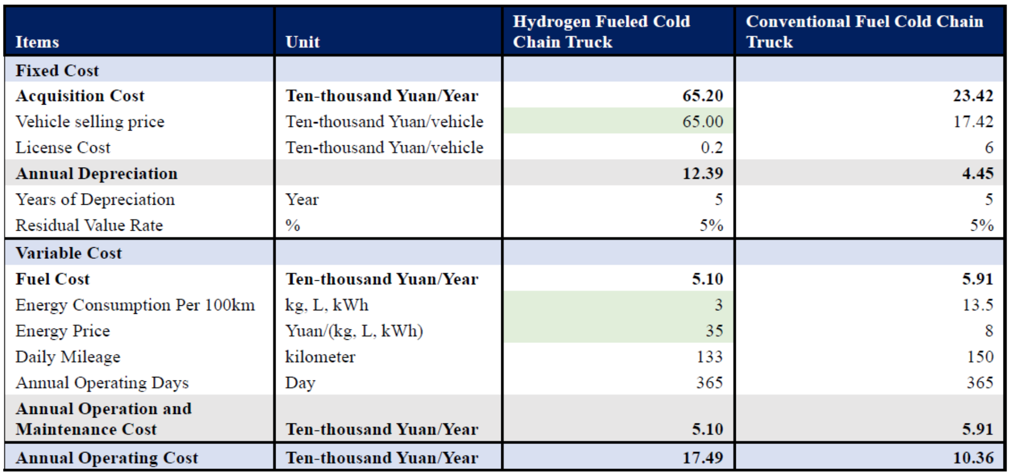
The author uses a 4.5-ton hydrogen fuel cell cold chain vehicle equipped with an 80 kW fuel cell system as an example to calculate the annual operating cost and assess potential cost-reduction strategies. This analysis involves comparing the hydrogen fuel cell vehicle with a conventional fuel cold chain vehicle. To comprehensively compare the economics of each technology route, this model does not currently factor in subsidies. However, subsidies will be addressed later as a policy measure to guide cost-reduction efforts. The key assumptions of the model for the current time node are outlined below:

1) Acquisition cost: Without considering subsidies, the price of a hydrogen fuel cell cold chain vehicle is 650,000 yuan with an annual license fee of 200,0 yuan. In comparison, the price of a conventional fuel cold chain vehicle is 174,200 yuan with an annual license fee of 60,000 yuan.
2) Vehicle depreciation: The vehicles are depreciated over a 5-year operational lifespan, assuming a 5% residual value at the end of that period.
3) Fuel cost:
    1) Energy consumption per 100 km: The hydrogen fuel cell cold chain vehicle consumes 3 kg of hydrogen per 100 km, while the conventional fuel cold chain vehicle consumes 13.5 liters of fuel per 100 km.
    2) Energy price: 35 yuan/kg for hydrogen, 8 yuan/L for conventional fuel.
    3) Driving range: The hydrogen fuel cell cold chain vehicles cover a distance of 133 km per day, while conventional fuel cold chain vehicles travel 150 km per day. Both types of vehicles operate 365 days per year.

1.2) Data Analysis

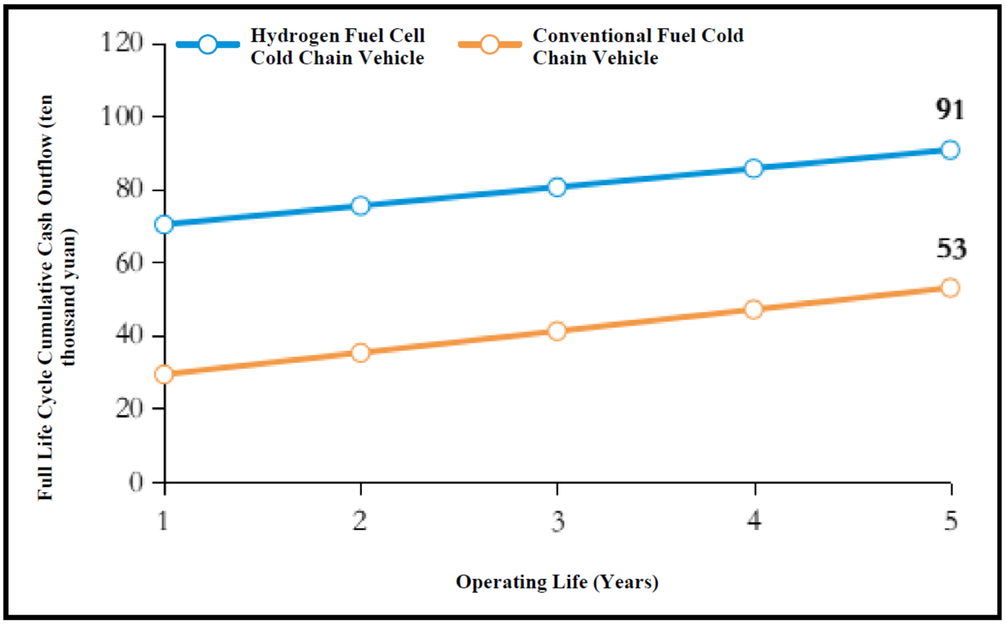
According to the model calculation, without considering subsidies, the current operating cost of hydrogen fuel cell cold chain vehicles is 174,900 yuan per year, which is significantly higher than that of conventional fuel logistics vehicles (103,600 yuan per year). This difference is primarily attributed to the higher initial purchase price of non-subsidized hydrogen fuel cell vehicles compared to conventional fuel logistics vehicles, despite their lower operation and maintenance costs. Therefore, the core factor enabling the application of hydrogen fuel cell cold chain vehicles is the reduction of acquisition costs (assuming constant profit margins, tied to manufacturing costs) and fuel costs (linked to hydrogen consumption per 100 km and hydrogen price) through technological progress and industrial scaling (refer to "Fig. 6.2.4 Comparison of Operating Costs of Cold Chain Vehicles under Different Technology Routes and "Fig. 6.2.5 Comparison of Full Life Cycle Cumulative Cash Outflows of Cold Chain Vehicle under Different Technology Routes").

Fig. 6.2.4 Comparison of Operating Costs of Cold Chain Vehicles under Different Technology Routes



Items	Unit	Hydrogen Fueled Cold Chain Truck	Conventional Fuel Cold Chain Truck
Fixed Cost			
Acquisition Cost	**Ten-thousand Yuan/Year**	**65.20**	**23.42**
Vehicle selling price	Ten-thousand Yuan/vehicle	65.00	17.42
License Cost	Ten-thousand Yuan/vehicle	0.2	6
Annual Depreciation		**12.39**	**4.45**
Years of Depreciation	Year	5	5
Residual Value Rate	%	5%	5%
Variable Cost			
Fuel Cost	**Ten-thousand Yuan/Year**	**5.10**	**5.91**
Energy Consumption Per 100km	kg, L, kWh	3	13.5
Energy Price	Yuan/(kg, L, kWh)	35	8
Daily Mileage	kilometer	133	150
Annual Operating Days	Day	365	365
Annual Operation and Maintenance Cost	**Ten-thousand Yuan/Year**	**5.10**	**5.91**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**17.49**	**10.36**

Fig. 6.2.5 Comparison of Full Life Cycle Cumulative Cash Outflows of Cold Chain Vehicle under Different Technology Routes



2) Operating Cost Reduction Model

2.1) Key Assumptions

For the primary assumptions underpinning the cost-reduction model for hydrogen fuel cell cold chain vehicles, please consult "A.1.2 Hydrogen fuel cell Logistics Vehicles" within the "2) Operating Cost Reduction Model" section. These assumptions are applicable to all scenarios involving hydrogen fuel cell logistics vehicles.

2.2) Data Analysis

Without considering the cost-reduction paths of conventional fuel cold chain vehicles, the projected operating cost of hydrogen fuel cell cold chain vehicles in 2030 is 77,400 yuan per year. This cost remains lower than the current operating costs of conventional fuel cold chain vehicles at 103,600 yuan per year. The primary reason is that by 2030, the vehicle price of hydrogen fuel cell cold chain vehicles is projected to be 287,200 yuan, slightly exceeding that of current conventional fuel cold chain vehicles, which stand at 234,200 yuan. However, the operations and maintenance (O&M) cost of hydrogen fuel cell cold chain vehicles in 2030 is predicted to be only 22,800 yuan per year, significantly lower than that of current conventional fuel cold chain vehicles, which amount to 59,100 yuan per year. In conclusion, solely focusing on the ultimate economic outcome, hydrogen fuel cell cold chain vehicles are anticipated to possess an inherent impetus to rival pure electric cold chain vehicles. However, to bolster their economic advantage, there is a pressing need to further decrease manufacturing costs (refer to "Fig. 6.2.6 & Fig. 6.2.7 Hydrogen Fuel Cell Cold Chain Vehicle Operaing Cost Reduction Calculation").

Fig. 6.2.6 Hydrogen Fuel Cell Cold Chain Vehicle Operating Cost Reduction Calculation

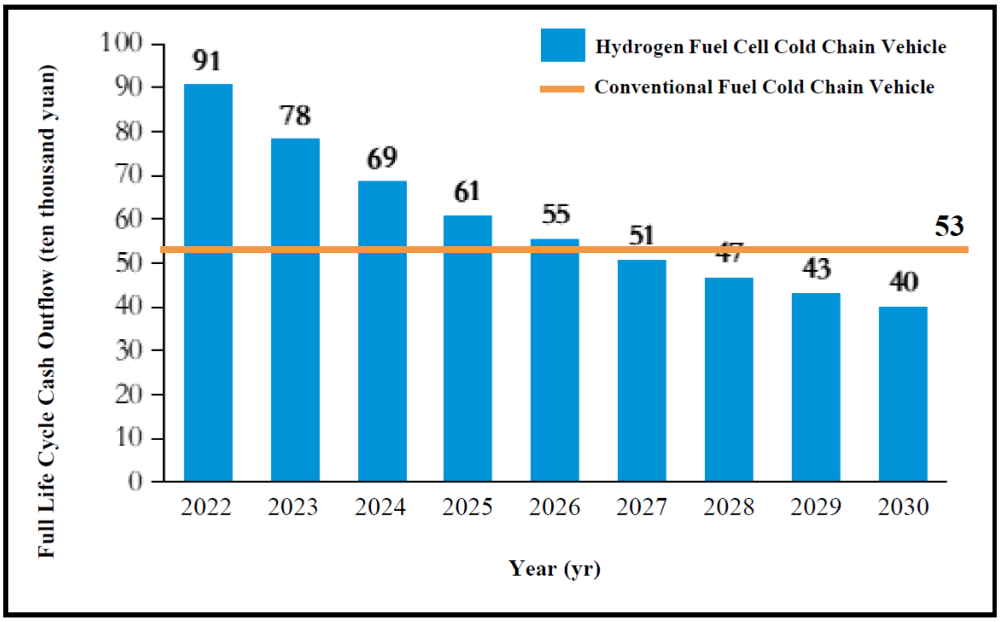
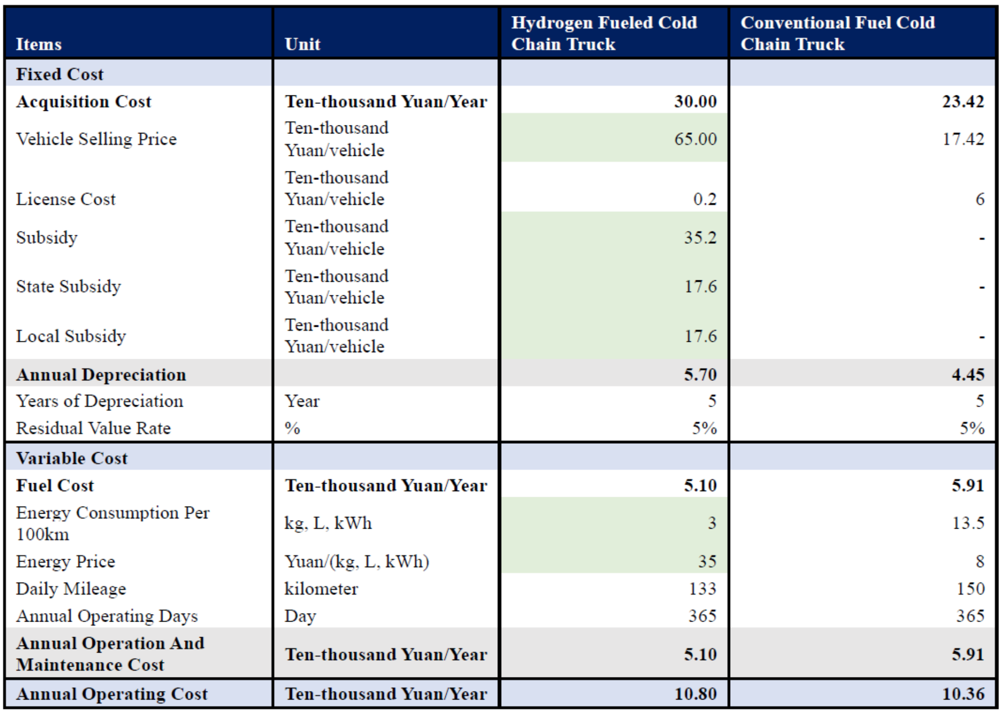


Fig. 6.2.7 Hydrogen Fuel Cell Cold Chain Vehicle Operating Cost Reduction Calculation

Items	Unit	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fixed Cost										
Manufacturing Cost	**Ten thousand yuan**	**52**	**44**	**38**	**33**	**30**	**28**	**26**	**24**	**23**
Fuel Cell System	Ten thousand yuan	30	23	17	13	10	8	7	5	4
Average Annual Reduction	*%*		*25%*	*25%*	*25%*	*20%*	*20%*	*20%*	*20%*	*20%*
Hydrogen Storage System	Ten thousand yuan	5.72	5	5	5	4	4	4	4	4
Average Annual Reduction	*%*		*7%*	*7%*	*7%*	*5%*	*5%*	*5%*	*5%*	*5%*
Battery System	Ten thousand yuan	2.60	2	2	2	2	2	2	2	2
Average Annual Reduction	*%*		*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
Acquisition Cost	**Ten thousand yuan**	**65**	**55**	**47**	**41**	**38**	**35**	**32**	**30**	**29**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	65	55	47	41	38	35	32	30	29
License Plate Price	Ten-thousand Yuan/vehicle	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Subsidy	Ten-thousand Yuan/vehicle	-	-	-	-	-	-	-	-	-
Subsidy Coefficient	-	-	-	-	-	-	-	-	-	-
Annual Depreciation	**Ten-thousand Yuan/Year**	**12.39**	**10.43**	**8.97**	**7.86**	**7.17**	**6.61**	**6.15**	**5.77**	**5.46**
Years of Depreciation	Year	5	5	5	5	5	5	5	5	5
Residual Value Rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Variable Cost										
Fuel Cost	**Ten-thousand Yuan/Year**	**5.10**	**4.68**	**4.28**	**3.90**	**3.55**	**3.20**	**2.88**	**2.57**	**2.28**
100km hydrogen consumption	kg/100km	3	3	3	3	3	3	2	2	2
Average Annual Reduction	*%*		*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*
Retail Price of Hydrogen	Yuan/kg	35	33	31	29	28	26	24	22	20
Daily mileage	kilometer	133	133	133	133	133	133	133	133	133
Annual Operating Days	Day	365	365	365	365	365	365	365	365	365
Annual Operation and Maintenance Cost	**Ten-thousand Yuan/Year**	**5.10**	**4.68**	**4.28**	**3.90**	**3.55**	**3.20**	**2.88**	**2.57**	**2.28**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**17.49**	**15.11**	**13.25**	**11.76**	**10.72**	**9.81**	**9.03**	**8.34**	**7.74**

Taking into account the current 1:1 ratio of national subsidies to local subsidies for hydrogen energy and the complete allocation of subsidies, hydrogen fuel cell cold chain vehicles have already reached cost parity with conventional fuel cold chain vehicles (refer to "Fig. 6.2.8 Comparison of Operating Costs of Cold Chain Vehicles under Different Technical Strategies (Considering Subsidies) ").

Fig. 6.2.8 Comparison of Operating Costs of Cold Chain Vehicles under Different Technical Strategies (Considering Subsidies)



Items	Unit	Hydrogen Fueled Cold Chain Truck	Conventional Fuel Cold Chain Truck
Fixed Cost			
Acquisition Cost	**Ten-thousand Yuan/Year**	**30.00**	**23.42**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	65.00	17.42
License Cost	Ten-thousand Yuan/vehicle	0.2	6
Subsidy	Ten-thousand Yuan/vehicle	35.2	-
State Subsidy	Ten-thousand Yuan/vehicle	17.6	-
Local Subsidy	Ten-thousand Yuan/vehicle	17.6	-
Annual Depreciation		**5.70**	**4.45**
Years of Depreciation	Year	5	5
Residual Value Rate	%	5%	5%
Variable Cost			
Fuel Cost	**Ten-thousand Yuan/Year**	**5.10**	**5.91**
Energy Consumption Per 100km	kg, L, kWh	3	13.5
Energy Price	Yuan/(kg, L, kWh)	35	8
Daily Mileage	kilometer	133	150
Annual Operating Days	Day	365	365
Annual Operation And Maintenance Cost	**Ten-thousand Yuan/Year**	**5.10**	**5.91**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**10.80**	**10.36**

6.3 Sinopec Kuqa Case: Cheap Photovoltaic Power Generation + Hydrogen Production from Electrolyzed Water in the Park

According to the Environmental Impact Assessment (EIA) Report for the Xinjiang Kuqa Green Hydrogen Demonstration Project, the first phase of the project involves a total investment of 2.962 billion yuan, of which 2.656 billion yuan will be allocated to construction. This investment encompasses several components, namely photovoltaic power generation, power transmission, water electrolysis, hydrogen production, hydrogen storage, and hydrogen transmission. The plan is to establish a new photovoltaic power station with an installed capacity of 300 MW (with an actual configuration of 355 MW accounting for inverter capacity) that will generate an average annual output of 618,006,700 kWh. Additionally, the project aims to incorporate 52 sets of alkaline electrolysis units to achieve an annual production of 20,000 tons of hydrogen. The hydrogen produced by the hydrogen plant is conveyed to the tank area for storage, amounting to 210,000 Nm^3 per year. Subsequently, it undergoes pressurization to 3.2 MPa via an external hydrogen compressor. This pressurized hydrogen is then transported via pipeline to Sinopec Tahe Refining at a rate of 28,000 Nm^3/h per year, where it serves as a chemical raw material. This process entirely supplants the usage of natural gas in the existing hydrogen plant. The project, scheduled for full completion and operation by June 2023, marks the inauguration of China's first 10,000-ton photovoltaic hydrogen production venture. It is anticipated to curtail carbon dioxide emissions by 485,000 tons annually (refer to "Fig. 6.3.1 Geographic Location of the Xinjiang Kuqa Green Hydrogen Demonstration Project", "Fig. 6.3.2 Xinjiang Kuqa Green Hydrogen Demonstration Project Photovoltaic Power Station", and "Fig.6.3.3 Xinjiang Kuqa Green Hydrogen Demonstration Project On-site Facilities").

Fig. 6.3.1 Geographic Location of the Xinjiang Kuqa Green Hydrogen Demonstration Project

Fig. 6.3.2 Xinjiang Kuqa Green Hydrogen Demonstration Project Photovoltaic Power Station

Fig. 6.3.3 Xinjiang Kuqa Green Hydrogen Demonstration Project On-site Facilities

According to the Environmental Impact Assessment (EIA) report of the project, the electrolyzer and other power-consuming equipment will utilize the electricity generated by the photovoltaic (PV) system during its operational hours. When the PV system is not generating electricity, a portion of green power will be procured to sustain the continuous operation of certain electrolyzers. Additionally, other power-consuming loads will also be supplied with green power purchased. Therefore, the integrated tariff is determined by combining the levelized cost of electricity (LCOE) with the grid tariff.

1) LCOE: According to the National Energy Administration, the annual utilization hours of PV in Class I and Class II areas in Xinjiang in 2021 were 1,597 hours and 1,455 hours, respectively. Combining this with the "China PV Industry Development Roadmap (2022-2023)", it is estimated that the levelized cost of electricity (LCOE) for the PV plant in the Kuqa project will be approximately 0.21 yuan/kWh.

2) Grid Tariff: As per the Xinjiang Development and Reform Commission, the tariff rates for large industrial catalogs at 110 kV and above are as follows: 0.1215 yuan/kWh for valley hours, 0.3360 yuan/kWh for level hours, and 0.5505 yuan/kWh for peak hours. Based on the ratio of valley, level, and peak hours set at 3:5:2, the comprehensive grid tariff for the Kuqa project is projected to be 0.31 yuan/kWh.
3) Comprehensive Electricity Price: Given that the project utilizes 60% of its electricity from the PV plant and 40% from the grid, the comprehensive electricity price is expected to be 0.254 yuan/kWh.

The Kuqa project leverages the cost-effective PV power generation resources in the Xinjiang region to lower the cost per kWh. By integrating this with large-scale water electrolysis for hydrogen production, the project has achieved initial economic feasibility in hydrogen production under the current comprehensive electricity price.

6.3.1 Model Key Assumptions

The primary factor influencing the cost of hydrogen production through water electrolysis is the price of electricity. This model uses a scenario with 52 units of 1,000 m^3/h alkaline water electrolyzers to analyze the cost of hydrogen production while varying the comprehensive electricity price. To comprehensively assess the economic viability of hydrogen production, this model excludes the consideration of subsidies for the time being. The key assumptions for the Kuqa project at the current time point are as follows:

1) Hydrogen Production Scale: The hydrogen production process involves using alkaline water electrolysis with each unit having a capacity of 1,000

m^3/h. The project comprises a total of 52 hydrogen production units, and these units operate for 4,308 hours annually.

2）Hydrogen Density: 0.0893 kg/m^3 in a standard case.

3）Fixed Cost:

- Depreciation Cost: Based on public bidding information, the Kuqa project has procured 52 alkaline water electrolyzers, each capable of producing 1,000 Nm^3/h of hydrogen. Additionally, the project has established 13 sets of electrolytic water gas-liquid separation facilities and 7 sets of hydrogen gas purification facilities. Based on the bidding prices from Cockerill, Longi Hydrogen Energy, and CSIC 718, the total equipment purchase cost for the Kuqa project is approximately 360 million yuan. Additionally, the cost of civil construction and equipment installation amounts to 63.53 million yuan, which will be depreciated over a period of 20 years with no salvage value, as detailed in "Fig. 6.3.1.1 Quotation of Shortlisted Suppliers for the Xinjiang Kuqa Green Hydrogen Demonstration Project".

Fig. 6.3.1.1 Quotation of Shortlisted Suppliers for the Xinjiang Kuqa Green Hydrogen Demonstration Project

Ranking	Bidder	Bidding price (yuan)	Bid evaluation price (yuan)	Quality
1	Cockerill Competitive	35,996	35,996	Qualified
2	Longi Hydrogen Energy	35,998	35,998	Qualified
3	CSIC 718	35,088	35,088	Qualified

- Labor Cost: According to the Environmental Impact Assessment (EIA) report of the project, the Kuqa project will hire an additional 16 staff members for hydrogen production through water electrolysis. The cost for these personnel is calculated at 80,000 yuan per person per year, resulting in a total annual expense of 1,280,000 yuan for staffing.

9) **Variable Cost:**

- Electrolysis Cost: Based on the public bidding information, the Kuqa project will procure 52 sets of electrolyzers from three enterprises: Cockerill Jingli, Longi Hydrogen Energy, and CSIC 718. According to the power consumption parameters provided by these enterprises, it is anticipated that the comprehensive power consumption of the hydrogen production system for the Kuqa project will be 4.6 kWh/Nm^3. Moreover, the price of electricity is expected to range from 0.1 to 0.6 yuan/kWh.
- Other Material Cost: Producing 1 m^3 of hydrogen necessitates the consumption of 1 kg of raw water, 1 kg of cooling water, and 0.0004 kg of KOH. The cost of water is 3.5 yuan per ton, while the price of KOH is 10 yuan per kg.

10) Carbon Reduction Benefit: According to information from Sinopec's official website, the Kuqa project is anticipated to diminish carbon dioxide emissions by 485,000 tons annually. The carbon price is calculated at 56 yuan/ton.

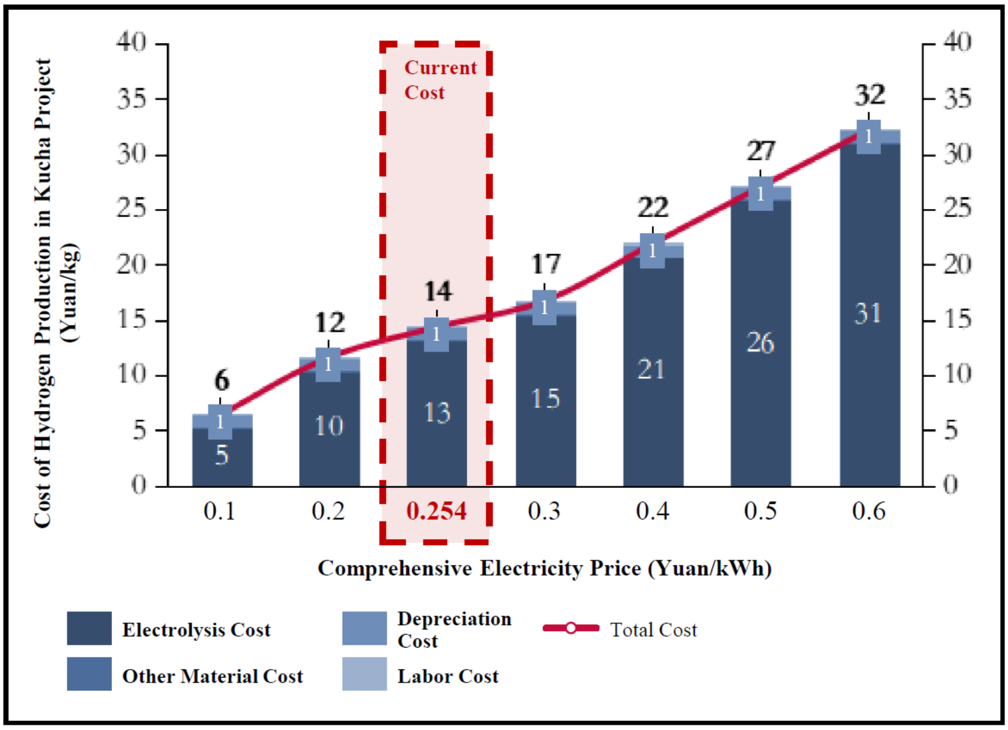
6.3.2 Modeling and Data Analysis

According to the measurements derived from the model, it has been established that the cost of hydrogen production in the Kuqa project demonstrates a positive correlation with the comprehensive electricity price. Excluding subsidies and carbon reduction benefits, the current comprehensive electricity price stands at 0.254 yuan/kWh. Correspondingly, the cost of hydrogen production is 14.31 yuan/kg, constituting 91% of the total electrolytic water hydrogen production cost. When the integrated electricity price increases to 0.6 yuan/kWh, the cost of hydrogen production increases to 32.16 yuan/kg. Taking into account carbon reduction benefits, the cost of hydrogen production for the Kuqa project is 12.95 yuan/kg when the electricity price is 0.254 yuan/kWh, and 30.80 yuan/kg when the electricity price is 0.6 yuan/kWh (refer to "Fig. 6.3.2.1 & Fig. 6.3.2.2 Sensitivity Calculation of Hydrogen Production Cost of the Kuqa Project to Comprehensive Electricity Price").

Fig. 6.3.2.1 Sensitivity Calculation of Hydrogen Production Cost of the Kuqa Project to Comprehensive Electricity Price

Comprehensive Electricity Price	Unit	0.1	0.2	0.254	0.3	0.4	0.5	0.6
Annual Hydrogen Production Capacity	**10,000 m^3**	**22,400**	**22,400**	**22,400**	**22,400**	**22,400**	**22,400**	**22,400**
Scale of Hydrogen Production Plant	m3/h	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Number of Hydrogen Production Units	Set	52	52	52	52	52	52	52
Annual Working Time	h	4,308	4,308	4,308	4,308	4,308	4,308	4,308
Hydrogen density	**kg/m^3**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**	**0.0893**
Fixed Cost	**Yuan/kg**	**1.12**	**1.12**	**1.12**	**1.12**	**1.12**	**1.12**	**1.12**
Depreciation Cost	**Yuan/kg**	**1.06**	**1.06**	**1.06**	**1.06**	**1.06**	**1.06**	**1.06**
Equipment Investment	Ten thousand yuan	36,000	36,000	36,000	36,000	36,000	36,000	36,000
Civil Construction and Equipment Installation	Ten thousand yuan	6,353	6,353	6,353	6,353	6,353	6,353	6,353
Years of Depreciation	Year	20	20	20	20	20	20	20
Labor Cost	**Yuan/kg**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**
Per Capita Salary	Ten-thousand Yuan /Person-Year	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Number of Employees	People	16	16	16	16	16	16	16
Variable Cost	**Yuan/kg**	**5.28**	**10.43**	**13.19**	**15.58**	**20.73**	**25.88**	**31.04**
Electrolysis Cost	**Yuan/kg**	**5.15**	**10.30**	**13.07**	**15.46**	**20.61**	**25.76**	**30.91**
Electricity Consumption	kWh/m3 H2	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Other Material Cost	**Yuan/kg**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**
Water Cost	**Yuan/kg**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**
Water Consumption	kg/m^3 H2	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Water Price	Yuan/m^3	3.5	3.5	3.5	3.5	3.5	3.5	3.5
KOH Cost	**Yuan/kg**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**
KOH Consumption	kg/m^3 H2	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
KOH Price	Yuan/kg	10	10	10	10	10	10	10
Total Cost	**Yuan/kg**	**6.40**	**11.55**	**14.31**	**16.70**	**21.85**	**27.01**	**32.16**
Carbon Reduction Gain	**Yuan/kg**	**1.36**	**1.36**	**1.36**	**1.36**	**1.36**	**1.36**	**1.36**
Carbon Reduction	Ten thousand tons	48.5	48.5	48.5	48.5	48.5	48.5	48.5
Carbon Price	Yuan/Ton	56.00	56.00	56.00	56.00	56.00	56.00	56.00
Total Cost (Considering Carbon Reduction Gain)	**Yuan/kg**	**5.04**	**10.19**	**12.95**	**15.34**	**20.50**	**25.65**	**30.80**

Fig. 6.3.2.2 Sensitivity Calculation of Hydrogen Production Cost of the Kuqa Project to Comprehensive Electricity Price



According to the model results outlined in 5.3.1 Hydrogen Production within this thesis, disregarding the expense of carbon capture, the cost of hydrogen production from coal ranges from approximately 7.61 to 14.42 yuan/kg. Similarly, the cost of hydrogen production from natural gas varies from about 7.16 to 22.17 yuan/kg. Additionally, the cost of industrial by-production of hydrogen falls within the range of approximately 9.3 to 22.4 yuan/kg, depending on different energy costs. After factoring in the cost of carbon capture, the cost of hydrogen production for the Kuqa project appears to be initially economical.

CHAPTER 7: CONCLUSIONS AND POLICY RECOMMENDATIONS

Through detailed modeling, this thesis conducts a comprehensive analysis of the operating costs associated with hydrogen fuel cell vehicles across various vehicle segments, including buses, logistics vehicles, heavy-duty trucks, and passenger vehicles, and compares these costs with those of conventional fuel vehicles and pure electric vehicles. Furthermore, the thesis offers reasonable predictions for cost reductions in core components and throughout the hydrogen industry supply chain. Ultimately, the analysis seeks to determine the feasibility of mass-producing hydrogen fuel cell vehicles within specific segments. Based on the model results, hydrogen fuel cell heavy-duty trucks and hydrogen fuel cell logistics vehicles, particularly in specialized scenarios such as cold-chain logistics, are projected to exhibit lower final operating costs compared to conventional fuel vehicles and pure electric vehicles. They are anticipated to possess a competitive advantage in terms of economic viability and are expected to be the first to be adopted in practical applications.

However, in addition to economic considerations, other factors such as energy diversification and the inherent advantages of hydrogen energy based on material systems, such as its low temperature performance and energy density, may further accelerate the widespread adoption of hydrogen fuel cell heavy-duty trucks. These vehicles can leverage their special advantages, including excellent low-temperature performance and extended range, to meet diverse application needs. Additionally, they can complement pure electric vehicles in various scenarios, fostering symbiotic relationships between different vehicle technologies.

7.1 Discussion of Research Results

Without factoring in subsidies, the current annual operating cost for conventional fuel heavy-duty trucks amounts to 591,600 yuan/year. Meanwhile, the operating cost for hydrogen fuel cell heavy-duty trucks stands at 724,200 yuan/year, and for pure electric heavy-duty trucks, it is 423,800 yuan/year. Therefore, supposing the annual operating costs of conventional fuel heavy-duty trucks and pure electric heavy-duty trucks remain constant, hydrogen fuel cell heavy-duty trucks present substitution opportunities when their annual operating costs fall below 423,800 yuan/year.

Likewise, excluding subsidies, the current annual operating costs for conventional fuel logistic vehicles amount to 199,700 yuan/year. Comparatively, the operating cost for hydrogen fuel cell logistic vehicles is 120,800 yuan/year, while for pure electric logistic vehicles, it is 87,600 yuan/year. Therefore, supposing the annual operating costs of conventional fuel logistic vehicles and pure electric logistics vehicles remain constant, hydrogen fuel cell logistic vehiclespresent substitution opportunities when their annual operating costs fall below 87,600 yuan/year.

The author predicts that achieving cost parity for hydrogen fuel cell vehicles will hinge on reducing two core factors: vehicle manufacturing costs and fuel expenses. The strategy for reducing manufacturing costs will primarily target core component costs, with a specific focus on decreasing the costs of fuel cell systems (projected average annual decrease of 25% from

2023 to 2025, and an average annual decrease of 20% from 2025 to 2030), hydrogen storage systems (anticipated average annual decrease of 7% from 2023 to 2025, and an average annual decrease of 5% from 2025 to 2030), and battery systems (expected average annual decrease of 5% from 2023 to 2030). This will be complemented by adjustments to subsidy policies, aligned with the "subsidies with awards" evaluation system for demonstration city clusters shown in Fig. 7.1.1. For instance, the national incentive funds for hydrogen fuel cell heavy-duty trucks with a fuel cell system rated power of 110 kW are capped at 462,000 yuan in 2022, with a national subsidy-to-local subsidy ratio of 1:1. Assuming a decrease in the subsidy coefficient from 1.1 to 0.2 from 2022 to 2030, the total subsidy is expected to decrease from 924,000 yuan to 168,000 yuan. Similarly, the national incentive fund for 4.5-ton 80 kW hydrogen fuel cell logistics vehicles in 2022 amounts to 176,000 yuan, with a presumed national subsidy-to-local subsidy ratio of 1:1. Assuming the same reduction in the subsidy coefficient, the total subsidy would decrease from 352,000 yuan to 64,000 yuan from 2022 to 2030. These adjustments are anticipated to lower the acquisition costs of hydrogen fuel cell heavy-duty trucks and logistics vehicles to less than 500,000 yuan in the medium to long term. The reduction in fuel costs will primarily focus on decreasing the price of hydrogen at the production and reducing hydrogen consumption per 100 km. Decreasing the price of hydrogen in production will involve cost reduction across the entire "preparation-storage-transportation-refueling" chain of upstream hydrogen. In the short term, the production of gray hydrogen will be predominant, considering the country's resource endowment. This includes hydrogen production from coal and industrial by-product hydrogen, which cost approximately 10 yuan/kg. Green hydrogen, mainly produced from alkaline water, serves as a supplementary source and costs between 25-40 yuan/kg. In the medium to long term, efforts will be directed towards the vigorous development of blue hydrogen (gray hydrogen with carbon capture technology, costing 15-20 yuan/kg) and new-energy power generation utilizing water electrolysis to produce hydrogen (costing 10-15 yuan/kg). Regarding the hydrogen storage and transportation segment, short-term strategies involve the use of 20 MPa long-tube trailers for hydrogen transportation, costing between 8-10 yuan/kg. In the medium to long term, the focus will shift towards developing 50 MPa tube trailer storage and transportation (costing 3-3.5 yuan/kg) and pipeline hydrogen transportation (costing 1-3 yuan/kg). Efforts will also be concentrated on reducing hydrogen refueling station construction costs and improving capacity utilization in the hydrogen refueling stage. This is anticipated to reduce refueling costs from 15-20 yuan to 8-10 yuan/kg. By incorporating the reduction in hydrogen consumption per 100 km through technological iteration, with an anticipated average annual decrease of 3% from 2022 to 2030, fuel costs are predicted to decrease below 30 yuan/kg.

It is important to emphasize that the outcomes of the model presented in this thesis heavily rely on the assumptions made, particularly the values of key assumptions. The current cost-reduction estimates are based on publicly available information, real case data, and the author's reasoned analysis. If the key assumptions change, there is a risk that the conclusions in this text could change as a result.

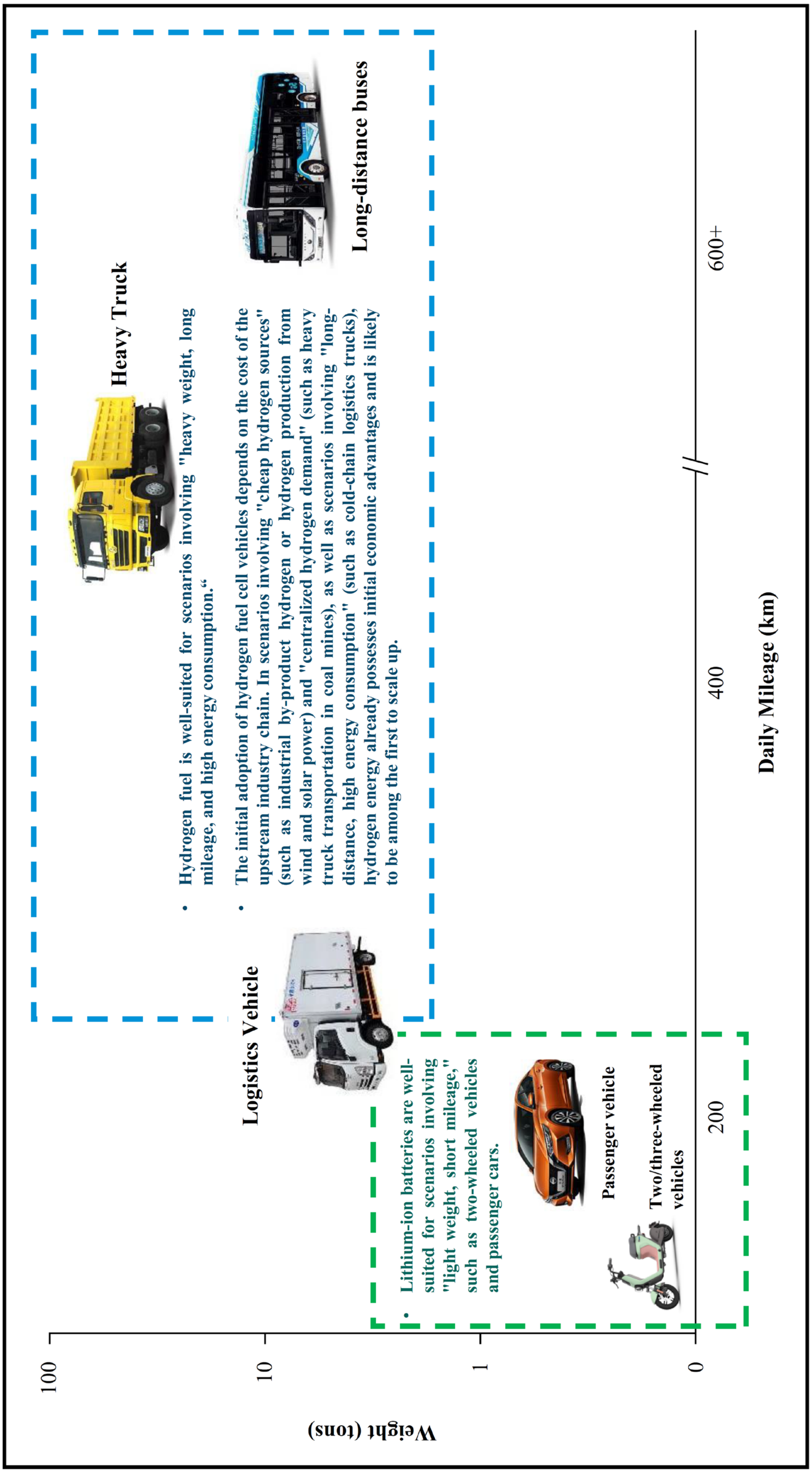
Former U.S. Secretary of Energy and Nobel Prize winner Steven Chu was interviewed in 2009 and suggested that achieving economic development through hydrogen energy requires addressing what he calls the "four wonders": First, the development of cheap sources of hydrogen, including short-term hydrogen production from coal/natural gas and medium- to long-term hydrogen production from alkaline water/PEM (proton exchange membrane); Second, the establishment of practical methods for hydrogen storage and transportation, such as short-term transportation via tube trailers and medium- to long-term pipeline transmission of hydrogen or its compounds (like alcohol and ammonia); Third, the advancement of mature hydrogen fuel cell technology; Fourth, the creation of a complete hydrogen infrastructure, which involves building hydrogen refueling stations and establishing hydrogen transportation pipelines. The findings and conclusions of this thesis reaffirm the four prerequisites outlined by Steven Chu. The potential success and adoption of hydrogen fuel cell vehicles hinge on technological advancements and the development of key components encompassing hydrogen fuel cell systems, and a robust hydrogen industry supply chain including hydrogen preparation, storage, transportation, and refueling infrastructure. This underscores the importance of breakthroughs in technology and cost reduction for hydrogen fuel cell vehicles to gain traction.

In summary, the author suggests that lithium-ion batteries are well-suited for applications requiring light weight and short mileage, such as two-wheeled vehicles and passenger vehicles. On the other hand, hydrogen fuel cell is considered more suitable for heavy vehicles, long-distance travel, and scenarios involving high energy consumption. The initial adoption of hydrogen fuel cell vehicles hinges on the cost dynamics of the upstream industrial chain. Specifically, scenarios characterized by "cheap hydrogen sources (such as industrial by-product hydrogen or hydrogen production from wind and solar) + concentrated hydrogen demand" (such as heavy-duty truck transportation in coal mines), and "long distance, high energy consumption" (for instance, cold-chain logistics vehicles), demonstrate preliminary economic advantages for hydrogen energy. It is anticipated that hydrogen energy will lead in mass production in these scenarios. For detailed information, please refer to Chapter 6 Application Case Analysis and "Fig. 7.1.2 Impact of Daily Mileage and Weight on Vehicle Battery Technology".

Fig. 7.1.1 Incentive Standard of the 2022 "Subsidies with Awards" Policy

System Power Range	Base Conversion Factor	Assumed System Power	Vehicle Incentive Amount ($10,000)			
			Design Gross Mass <12 tons	Design Gross Mass 12-25 tons	Design Gross Mass 25-31 tons	Design Gross Mass >31 tons
(12 Tons Or More) Heavy Duty Trucks And (10m Or More) Large Buses	$Y = (p-50) \times 0.03+1$ $Y = 2.8$ for $p \geq 110$	50	11.00	12.10	14.30	16.50
		60	14.30	15.73	18.59	21.45
		110	30.80	33.88	40.04	46.20
Light Buses and Vans	$Y = (p-50) \times 0.02+1$ $Y = 1.6$ for $p \geq 80$	50	11.00	12.10	14.30	16.50
		60	13.20	14.52	17.16	19.80
		80	17.60	19.36	22.88	26.40
Passenger Vehicle	$Y = (p-50) \times 0.03+1$ $Y = 1.9$ for $p \geq 80$	50	11.00	12.10	14.30	16.50
		60	14.30	15.73	18.59	21.45
		80	20.90	22.99	27.17	31.35

Fig. 7.1.2 Influence of Daily Driving Range and Weight on Vehicle Battery Technology Selection



- Hydrogen fuel is well-suited for scenarios involving "heavy weight, long mileage, and high energy consumption."“
- The initial adoption of hydrogen fuel cell vehicles depends on the cost of the upstream industry chain. In scenarios involving "cheap hydrogen sources" (such as industrial by-product hydrogen or hydrogen production from wind and solar power) and "centralized hydrogen demand" (such as heavy truck transportation in coal mines), as well as scenarios involving "long-distance, high energy consumption" (such as cold-chain logistics trucks), hydrogen energy already possesses initial economic advantages and is likely to be among the first to scale up.

- Lithium-ion batteries are well-suited for scenarios involving "light weight, short mileage," such as two-wheeled vehicles and passenger cars.

7.2 Other Influencing Factors

This thesis thoroughly examines the economic aspects across various technical strategies; however, the initial adoption of hydrogen energy is influenced by multiple factors across different dimensions. The author argues that economics plays a critical role in determining whether hydrogen fuel cell vehicles have the opportunity to start from scratch. Meanwhile, other factors influence the rate or steepness of the adoption curve for hydrogen fuel cell vehicles during this transition. Apart from cost considerations, hydrogen provides energy diversity and possesses unique material properties, such as a low-temperature advantage and high energy density. These additional benefits will contribute significantly to accelerating the adoption rate of hydrogen fuel cell vehicles.

For example, considering energy density and low-temperature performance, lithium batteries typically have an energy density of no more than 500 Wh/kg, limiting the range of pure electric vehicles and making them suitable primarily for short-distance transportation within cities. Therefore, lithium batteries have taken the lead in the passenger vehicle field. Furthermore, lithium battery power tends to degrade at low temperatures, leading to reduced performance. The need for car and battery heating to counteract this issue consumes significant amounts of power, further reducing the overall range of electric vehicles. While addressing the former issue can be achieved through the integration of battery thermal management functions, and the latter can be mitigated to some extent by incorporating a heat pump into the vehicle and opting for alternative refrigerants, lithium battery materials themselves do not inherently surpass hydrogen energy in terms of advantages. According to data from 2022, China's average penetration rate of new-energy vehicles stands at 25.22%. This rate varies significantly across different regions, with South China reaching a penetration rate of 32.00% and East China at 28.46%. In contrast, the Northeast region reports a much lower penetration rate of only 9.73%, and Northwest China follows at 15.39%, with significantly higher rates in the southern regions compared to the northern ones. In comparison, hydrogen has an energy density of 33.6 kWh/kg, which is 60-70 times higher than that of lithium batteries. However, the current challenge with hydrogen fuel cell vehicles is the limited working pressure of hydrogen storage bottles, which is only 35 MPa. This results in a lower volumetric energy density. Nevertheless, when looking at the overall comparison, hydrogen fuel cell vehicles still outperform pure electric vehicles. In the future, there is an expectation to develop storage methods using 70 MPa gaseous hydrogen or liquid hydrogen. Hydrogen fuel cell vehicles exhibit superior performance at low temperatures and are anticipated to lead the way, especially in specialized scenarios such as heavy-duty trucks and logistics vehicles, particularly those involved in cold-chain logistics.

Furthermore, the author suggests that the use of hydrogen energy in the automotive sector is just the beginning. In the future, as industrial chain costs continue to decrease, hydrogen or its compounds (like alcohol or ammonia) may serve as pivotal energy storage and transportation mediums. Additionally, their applications in energy and chemical sectors could emerge as the primary directions for the development of hydrogen energy. Especially in western China, where there are abundant wind and solar resources, the problem of wind and solar power curtailment is significant. By converting renewable electricity into hydrogen energy, it helps address the issue of utilizing local green power effectively. Hydrogen or its compounds (such as alcohol and ammonia) generated from green power can serve multiple purposes. Firstly, they can be transported to regions with high energy demand in central and eastern China through the establishment of pipeline networks. Secondly, these compounds can be utilized in various applications within the energy and chemical industries, including coal chemical processes, petroleum refining, metallurgy, and other industrial operations. They can function as fuels, raw materials, and reductants, supporting a wide range of industrial activities. Hydrogen can be stored and transported more cost-effectively in the form of compounds such as alcohol or ammonia compared to hydrogen itself. However, the green alcohol and green ammonia industries are still in their infancy and currently more expensive than conventional synthesis methods. Further development is needed to make them more viable.

7.3 Policy Recommendations and Outlook

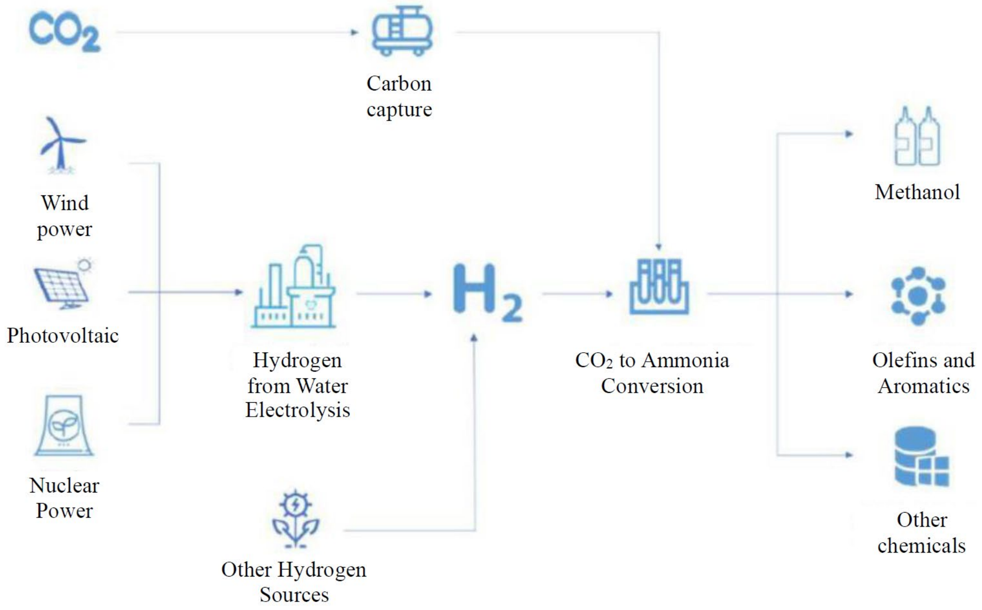
Based on the conclusions of this thesis, the author suggests advancing the promotion of hydrogen energy through targeted policy measures. This includes emphasizing support for application scenarios that offer economic benefits, such as heavy-duty trucks and cold-chain logistics vehicles. Drawing on historical subsidy programs and policies from the lithium battery industry, the author recommends increasing national and local support for hydrogen fuel cell vehicles and the broader hydrogen energy industry.

The hydrogen energy industry is on the brink of rapid expansion. Public data indicates steady growth in the hydrogen fuel cell vehicle sector, with cumulative national sales from 2015 to the first half of 2023 reaching 14,715 units. In the first half of this year alone, cumulative sales totaled 2,410 units, representing a 73.5% increase. The "production, storage, and transportation, and refueling" stages in the hydrogen energy industry driven by the downstream growth is set to accelerate, paving the way for significant progress. The major bottlenecks that have been limiting the industry's development are on the verge of a breakthrough. In China, the hydrogen production sector has made significant strides with the successful implementation of the first 10,000-ton green hydrogen project. The Three Gorges Jungar Banner Naresong Photovoltaic Hydrogen Production Demonstration Project and the Sinopec Xinjiang Kuqa Photovoltaic Hydrogen Production Demonstration Project have both been launched and are now operational. These projects have demonstrated initial economic benefits. At the storage and transportation stage, China has made notable advancements with the successful supply of gas from its first medium and long-distance hydrogen pipeline. This pipeline, which supports the Yumen Oilfield photovoltaic hydrogen production demonstration project, extends 5.77 km and has a design capacity of 7,000 tons per year. Breakthroughs have also been achieved in long-distance hydrogen pipeline transmission. Sinopec's Western Hydrogen Eastward Project, the country's longest hydrogen transmission line, has been formally launched. With a total length of over 400 km, it is China's first inter-provincial, large-scale, long-distance pure hydrogen transmission pipeline. The first phase of the project boasts a capacity of 100,000 tons per year, with potential for long-term upgrades up to 500,000 tons per year. Ports have been strategically positioned along the pipeline to facilitate access to potential hydrogen sources. In China, the development of hydrogen refueling infrastructure is rapidly accelerating. A total of 385 hydrogen refueling stations have been built nationwide, representing 40% of the global total and placing China first in the world in terms of hydrogen refueling infrastructure. In addition to the rising number of refueling stations, regions such as Guangdong, Shandong, Tangshan in Hebei, Wuhan in Hubei, and Shanghai's Lingang area have seen breakthroughs in technical specifications and policies related to non-chemical park-based hydrogen production. At the same time, the core technology of hydrogen fuel cells has seen steady improvement, and the localization of key components has increased significantly. Core components such as electric stacks, membrane electrodes, and bipolar plates have been independently developed, while proton exchange membranes, carbon paper, and catalysts are undergoing localization verification. The performance of hydrogen fuel cell products continues to improve, while prices keep falling. For instance, hydrogen fuel cell systems currently offer over 200 kW of power, with a power density exceeding 4.0 kW/L. Additionally, these systems can start at low temperatures as cold as -30 °C, and their price is now less than 4,000 yuan per kW. The market is driven by demonstration city clusters, which progressively expand to foster a multi-polarized approach. In 2022, Beijing, Shanghai, and the Henan region dominated the demonstration city cluster market, accounting for 45.9% of the market share. Meanwhile, lower-priced hydrogen markets such as Shanxi, Shaanxi, and Hebei made up 11% of the market. These regions have an abundance of industrial by-products that supply hydrogen resources, keeping the price of hydrogen below 20 yuan per kilogram. Additionally, the renewable energy market is achieving a hydrogen-electricity coupling, enabling the consumption of green hydrogen, which holds long-term strategic significance.

The hydrogen energy industry is currently grappling with several challenges. First, there is a disconnect between the cost and performance of hydrogen fuel cell products and the actual market demand. Customers are looking for products that offer "low cost, low hydrogen consumption, and high reliability." Second, the industry is experiencing a surge in market entrants, with a total of 54 system companies as of 2022, representing a 54% year-on-year increase. This rapid expansion has led to issues such as "index competition, quick starts, and price wars." Finally, the promotion and application of hydrogen fuel cell vehicles are hindered by an immature industry ecosystem. System companies must navigate challenges related to hydrogen production, vehicle integration, vehicle procurement, vehicle application, hydrogen refueling, and driving path of vehicle. The division of labor across the hydrogen fuel cell supply chain is unclear and requires cross-sector collaboration to address these complexities. In the long run, the author believes that companies that have "innovative products, large-scale manufacturing capabilities, cost-efficiency, and strong customer loyalty" are poised to become industry leaders and drive industry growth.

Looking ahead, the author believes that the transportation sector represents just a small fraction of the potential applications for hydrogen energy. Hydrogen can be utilized in various other scenarios, such as serving as a medium for energy storage to harness excess wind and solar energy, or acting as a fuel, raw material, or reducing agent in the industrial sector. This broad use of hydrogen offers a crucial pathway to deep decarbonization that cannot be achieved through electrification alone (refer to "Fig. 7.3.1 Carbon Dioxide Coupled Development Path of Green Hydrocarbon Chemical Schematic Diagram"). Moreover, hydrogen applications in the chemical industry involve larger-scale hydrogen production and more concentrated demand compared to individual hydrogen fuel cell vehicle projects. This creates significant economic advantages and makes the use of hydrogen in the chemical sector a more economically attractive option.

Fig. 7.3.1 Carbon Dioxide Coupled Development Path of Green Hydrocarbon Chemical Schematic Diagram



APPENDICES

Following the methodology of building a cost and cost reduction model for heavy-duty trucks presented in this thesis, the text goes on to elaborate on the operating costs of vehicles in other application scenarios (buses, delivery trucks, passenger vehicles) and different technical routes (hydrogen fuel cell, conventional fuel, pure electric vehicles). It also conducts a horizontal comparison across these different scenarios and technologies. By examining the future cost reduction trajectories of hydrogen fuel cell vehicles in each of the application scenarios mentioned above, we can assess the likelihood of hydrogen fuel cell vehicles gaining significant traction in any given scenario.

A.1 Analysis of Vehicle Operating Cost and Cost Reduction Modeling

A.1.1 Hydrogen Fuel Cell Buses

1) Operating Cost Model

1.1) Key Assumptions

Hydrogen fuel cell buses are primarily used in application scenarios including public transportation, highway transportation, and commuter services. Public bidding information indicates that the average acquisition cost of hydrogen fuel cell buses ranges from 2 to 3 million yuan per vehicle. These buses typically have a fuel cell system with a rated power of 45 to 65 kW. The author uses a 10.5-meter hydrogen fuel cell bus equipped with a 50 kW fuel cell system as an example to calculate the annual operating cost and the potential cost reduction path. This is then compared with conventional fuel buses and pure electric buses. To comprehensively compare the economics of each technology route, this model does not currently factor in subsidies. However, subsidies will be addressed later as a policy measure to guide cost reduction efforts. The key assumptions of the model for the current time node are outlined below:

1) Acquisition cost: Without considering subsidies, the cost of a hydrogen fuel cell bus is 2.2 million yuan, while a conventional fuel bus costs 500,000 yuan, and a pure electric bus costs 800,000 yuan.

2) Vehicle depreciation: The vehicles are depreciated over an 8-year operational lifespan, assuming a 5% residual value at the end of that period.

3) Fuel cost:

- Energy consumption per 100 km: A hydrogen fuel cell bus consumes 7 kg of hydrogen per 100 km, a conventional fuel bus consumes 20 liters of fuel per 100 km, and a pure electric bus consumes 70 kWh of electricity per 100 km.
- Energy price: Hydrogen is priced at 35 yuan per kilogram, conventional fuel is priced at 8 yuan per liter, and electricity is priced at 0.67 yuan per kilowatt-hour.
- Driving range: 200 km per day, 360 days of operation per year.

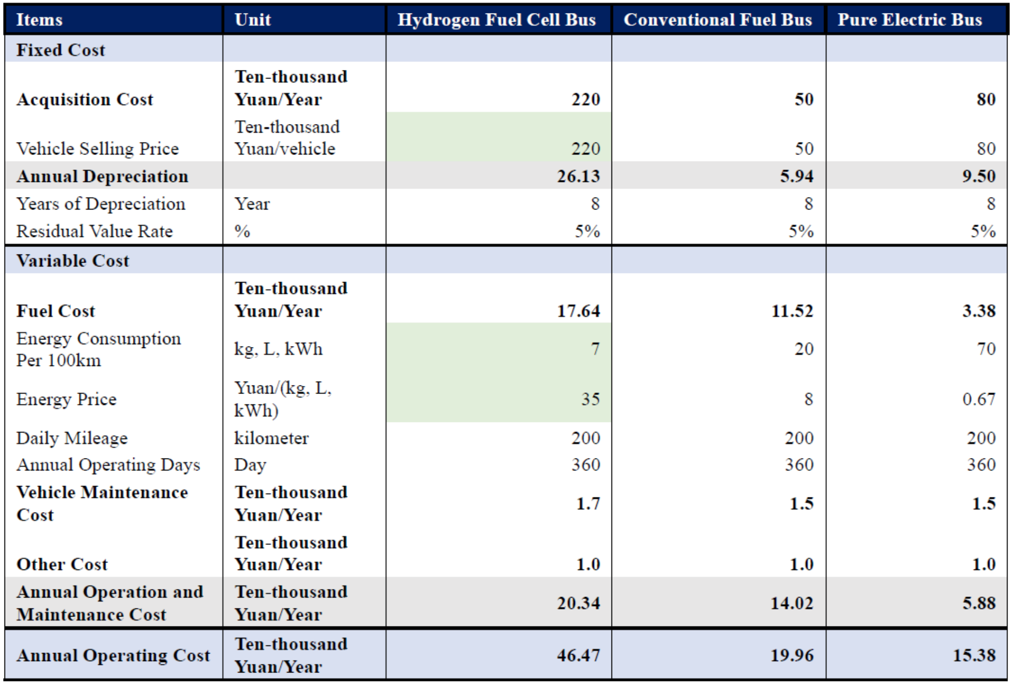
4) Vehicle maintenance fee: The maintenance cost is 17,000 yuan per year for hydrogen fuel cell buses, while it is 15,000 yuan per year for conventional fuel buses and pure electric buses.

5) Other costs: all 10,000 yuan/year. Moreover, the purchase contract includes an 8-year full life-cycle warranty, eliminating any additional maintenance costs during this period.

1.2) Data Analysis

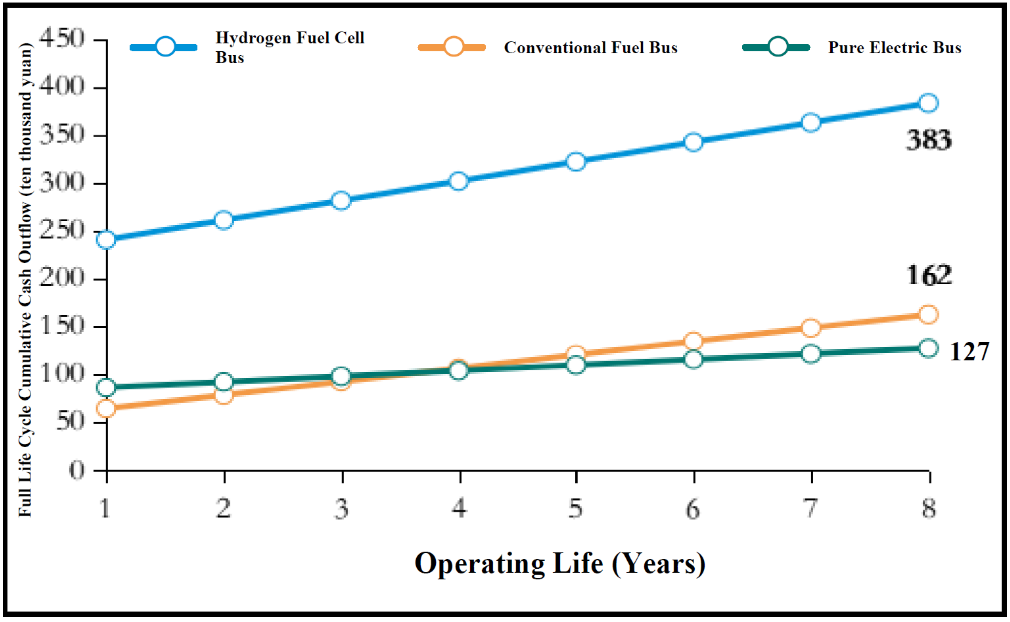
The model calculates that, without considering subsidies, the current annual operating cost of hydrogen fuel cell buses is 464,700 yuan, significantly higher than that of conventional fuel buses at 199,600 yuan per year and pure electric buses at 153,800 yuan per year. This is primarily due to the higher selling price of unsubsidized hydrogen fuel cell vehicles and the elevated cost of fuel compared to conventional fuel buses and pure electric buses. In comparison, although the initial acquisition cost of pure electric buses is higher, their lower operation and maintenance costs mean that the cumulative cash flow expenditure becomes lower than that of conventional fuel buses in the fourth year of operation. From there, the economic advantage of pure electric buses grows year by year, providing an internal drive for their adoption as a replacement. Therefore, the core factor enabling the application of hydrogen fuel cell buses is the reduction of acquisition costs (assuming constant profit margins, tied to manufacturing costs) and fuel costs (linked to hydrogen consumption per 100 km and hydrogen price) through technological progress and industrial scaling (refer to "Fig. A.1.1.1 Comparison of Bus Operating Costs under Different Technology Routes" and "Fig. A.1.1.2 Comparison of Full Life Cycle Cumulative Cash Outflows of Buses under Different Technology Routes" for more details).

Fig. A.1.1.1 Comparison of Bus Operating Costs under Different Technology Routes



Items	Unit	Hydrogen Fuel Cell Bus	Conventional Fuel Bus	Pure Electric Bus
Fixed Cost				
Acquisition Cost	**Ten-thousand Yuan/Year**	**220**	**50**	**80**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	220	50	80
Annual Depreciation		**26.13**	**5.94**	**9.50**
Years of Depreciation	Year	8	8	8
Residual Value Rate	%	5%	5%	5%
Variable Cost				
Fuel Cost	**Ten-thousand Yuan/Year**	**17.64**	**11.52**	**3.38**
Energy Consumption Per 100km	kg, L, kWh	7	20	70
Energy Price	Yuan/(kg, L, kWh)	35	8	0.67
Daily Mileage	kilometer	200	200	200
Annual Operating Days	Day	360	360	360
Vehicle Maintenance Cost	**Ten-thousand Yuan/Year**	**1.7**	**1.5**	**1.5**
Other Cost	**Ten-thousand Yuan/Year**	**1.0**	**1.0**	**1.0**
Annual Operation and Maintenance Cost	**Ten-thousand Yuan/Year**	**20.34**	**14.02**	**5.88**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**46.47**	**19.96**	**15.38**

Fig. A.1.1.2 Comparison of Full Life Cycle Cumulative Cash Outflows of Buses under Different Technology Routes



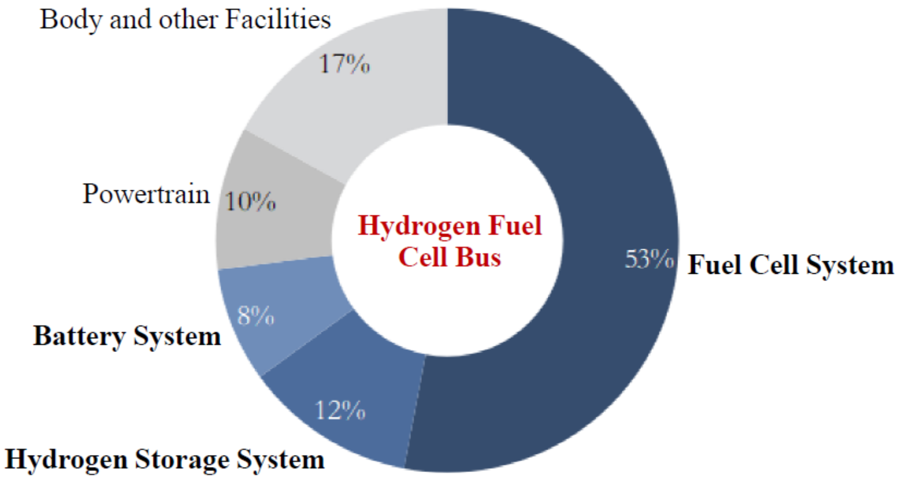
2) Operating Cost Reduction Model

2.1) Key Assumptions

The manufacturing cost of hydrogen fuel cell buses is primarily driven by the cost of upstream components. The core components of hydrogen fuel cell buses include the fuel cell system (53% of the cost), hydrogen storage system (12%), and battery system (8%). These components are still in the early stages of industrial research and development, indicating significant potential for future cost reduction. The drive system (10%), as well as the body and other facilities (17%), are more established technologies that have been adapted from conventional fuel buses. (Refer to Fig. A.1.1.3 for the cost structure of a 10.5-meter hydrogen fuel cell bus.) The operation and maintenance costs are primarily determined by the fuel cost, which is directly related to hydrogen consumption per 100 km and the price of hydrogen refueling. (Refer to 5.3 Analysis of Hydrogen Industry Costs and Cost Reduction Model" for more information.)

The key assumptions of the cost-reduction model for hydrogen fuel cell buses can be found in the chapter on hydrogen fuel cell heavy-duty trucks. These assumptions apply to all scenarios involving hydrogen fuel cell vehicles.

Fig. A.1.1.3 Cost Structure of a 10.5-meter Hydrogen Fuel Cell Bus



2.2) Data Analysis

Without considering the cost-reduction paths of conventional fuel buses and pure electric buses, the projected operating cost of hydrogen fuel cell buses in 2030 is 229,100 yuan per year. This cost remains higher than the current operating costs of conventional fuel buses at 199,600 yuan per year and pure electric buses at 153,800 yuan per year. The primary reason for the higher operating cost of hydrogen fuel cell buses in 2030 is attributed to their vehicle selling price, which is projected to be 1.04 million yuan. This selling price significantly exceeds that of current conventional fuel buses (500,000 yuan) and pure electric buses (800,000 yuan). However, the operations and maintenance (O&M) cost of hydrogen fuel cell buses in 2030 is estimated to be 106,000 yuan/year, which is lower than the current O&M cost of conventional fuel buses (140,200 yuan/year), but significantly higher than the O&M cost of pure electric buses ($58,800 per year). In summary, when considering only the overall economic aspects, hydrogen fuel cell buses lack the inherent competitive advantage to rival pure electric buses (refer to "Fig.

A.1.1.4 & Fig. A.1.1.5 Hydrogen fuel cell Buses Operating Cost Reduction Calculation" for more details).

Fig. A.1.1.4 Hydrogen Fuel Cell Buses Operating Cost Reduction Calculation

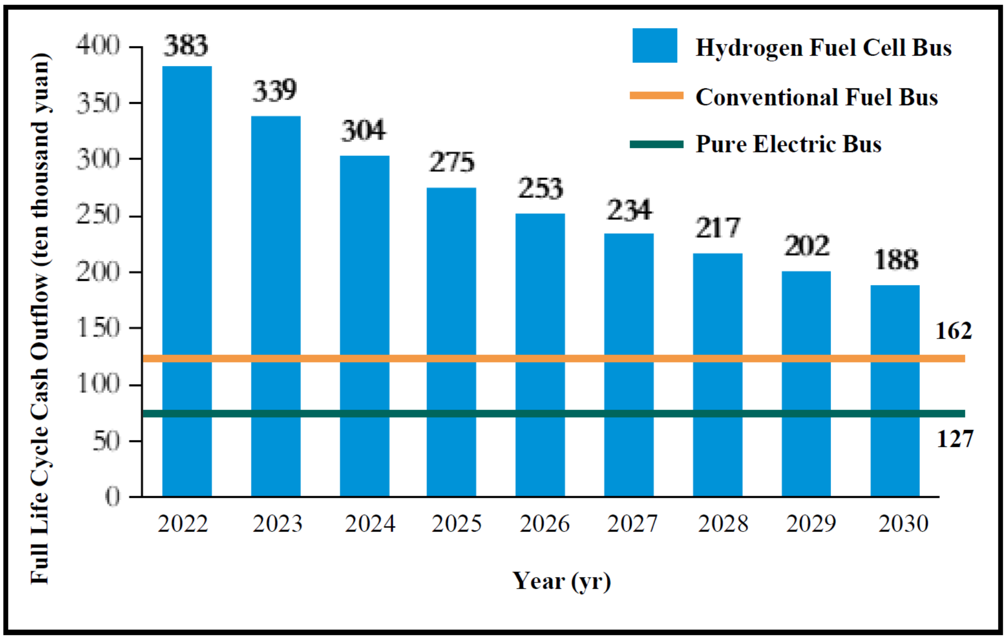


Fig. A.1.1.5 Hydrogen Fuel Cell Buses Operating Cost Reduction Calculation

Items	Unit	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fixed Cost										
Manufacturing Cost	**Ten thousand yuan**	**176**	**150**	**131**	**116**	**107**	**99**	**93**	**87**	**83**
Fuel Cell System	Ten thousand yuan	93	70	52	39	31	25	20	16	13
Average Annual Reduction	*%*		*25%*	*25%*	*25%*	*20%*	*20%*	*20%*	*20%*	*20%*
Hydrogen Storage System	Ten thousand yuan	21	20	18	17	16	15	15	14	13
Average Annual Reduction	*%*		*7%*	*7%*	*7%*	*5%*	*5%*	*5%*	*5%*	*5%*
Battery System	Ten thousand yuan	14	13	13	12	11	11	10	10	9
Average Annual Reduction	*%*		*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
Acquisition Cost	**Ten thousand yuan**	**220**	**188**	**164**	**145**	**133**	**124**	**116**	**109**	**104**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	220	188	164	145	133	124	116	109	104
Subsidy	Ten-thousand Yuan/vehicle	-	-	-	-	-	-	-	-	-
Subsidy Coefficient	-	-	-	-	-	-	-	-	-	-
Annual Depreciation	**Ten-thousand Yuan/Year**	**26.1**	**22.3**	**19.4**	**17.2**	**15.8**	**14.7**	**13.7**	**13.0**	**12.3**
Years of Depreciation	Year	8	8	8	8	8	8	8	8	8
Residual Value Rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Variable Cost										
Fuel Cost	**Ten-thousand Yuan/Year**	**18**	**16**	**15**	**14**	**12**	**11**	**10**	**9**	**8**
100km Hydrogen Consumption	kg/100km	7.0	6.8	6.6	6.4	6.2	6.0	5.8	5.7	5.5
Average Annual Reduction	*%*		*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*
Retail Price of Hydrogen	Yuan/kg	35	33	31	29	28	26	24	22	20
Daily Mileage	kilometer	200	200	200	200	200	200	200	200	200
Annual Operating Days	Day	360	360	360	360	360	360	360	360	360
Vehicle Maintenance Cost	**Ten-thousand Yuan/Year**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Other Cost	**Ten-thousand Yuan/Year**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Annual Operation And Maintenance Cost	**Ten-thousand Yuan/Year**	**20**	**19**	**18**	**16**	**15**	**14**	**13**	**12**	**11**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**46**	**41**	**37**	**33**	**31**	**28**	**26**	**25**	**23**

A.1.2 Hydrogen Fuel Cell Logistics Vehicles

1) Operating Cost Model

1.1) Key Assumptions

Hydrogen fuel cell logistics vehicles primarily encompass application scenarios such as van-type transportation trucks, refrigerated trucks, postal trucks, and insulated trucks. Public bidding information indicates that most hydrogen fuel cell logistics vehicles range in weight from 7.5 to 9 tons, and the rated power of the fuel cell system is typically between 30 and 60 kW. The author uses a 9-ton hydrogen fuel cell logistics vehicle equipped with a 50 kW fuel cell system as an example to calculate the annual operating cost and potential cost-reduction path. This cost analysis is then compared with the costs of conventional fuel logistics vehicles and pure electric logistics vehicles. To comprehensively compare the economics of each technology route, this model does not currently factor in subsidies. However, subsidies will be addressed later as a policy measure to guide cost reduction efforts. The key assumptions of the model for the current time node are outlined below:

1） Acquisition cost: Without considering subsidies, the cost of a hydrogen fuel cell logistics vehicle is 1.1 million yuan, a conventional fuel logistics vehicle costs 200,000 yuan, and a pure electric logistics vehicle costs 400,000 yuan.

2） Vehicle depreciation: The vehicles are depreciated over a 8-year operational lifespan, assuming a 5% residual value at the end of that period.

3） Fuel cost:

- Energy consumption per 100 km: A hydrogen fuel cell logistics vehicle consumes 2.8 kg of hydrogen per 100 km, while a conventional fuel logistics vehicle consumes 20 liters of fuel per 100 km. A pure electric logistics vehicle consumes 50 kWh of electricity per 100 km.
- Energy price: The cost of hydrogen is 35 yuan per kg, conventional fuel costs 8 yuan per liter, and electricity is priced at 0.67 yuan per kWh.
- Driving range: 150 km per day, 300 days of operation per year.

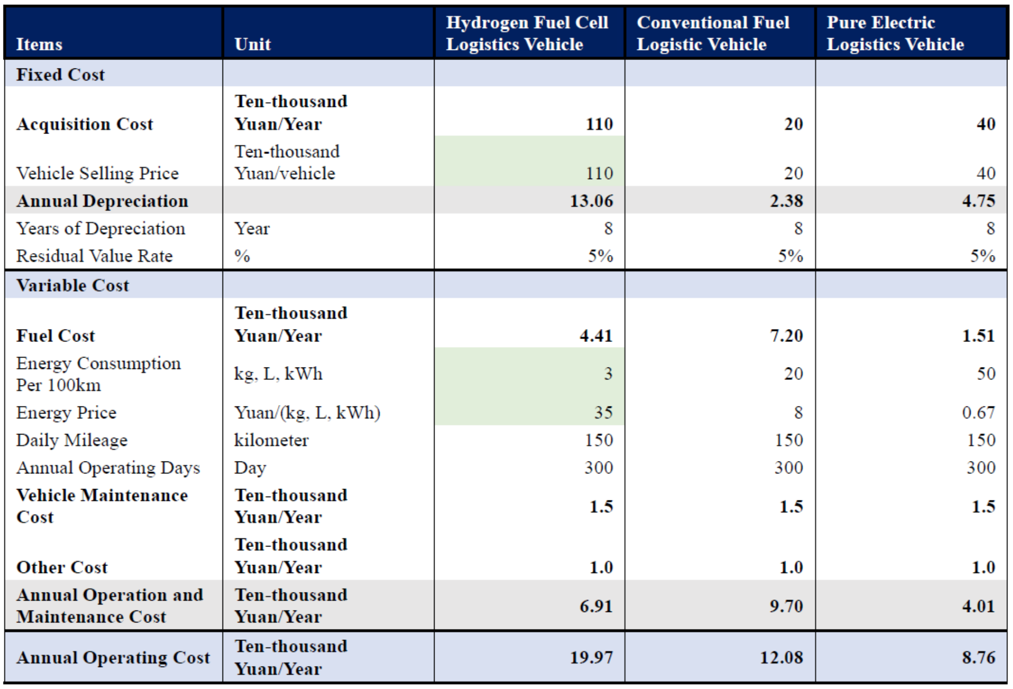
4）Vehicle maintenance fee: All 15,000 yuan/year.

5）Other costs: 1 million yuan/year for all. Furthermore, the purchase contract includes a 8-year full life-cycle warranty, with no additional cost for maintenance.

1.2) Data Analysis

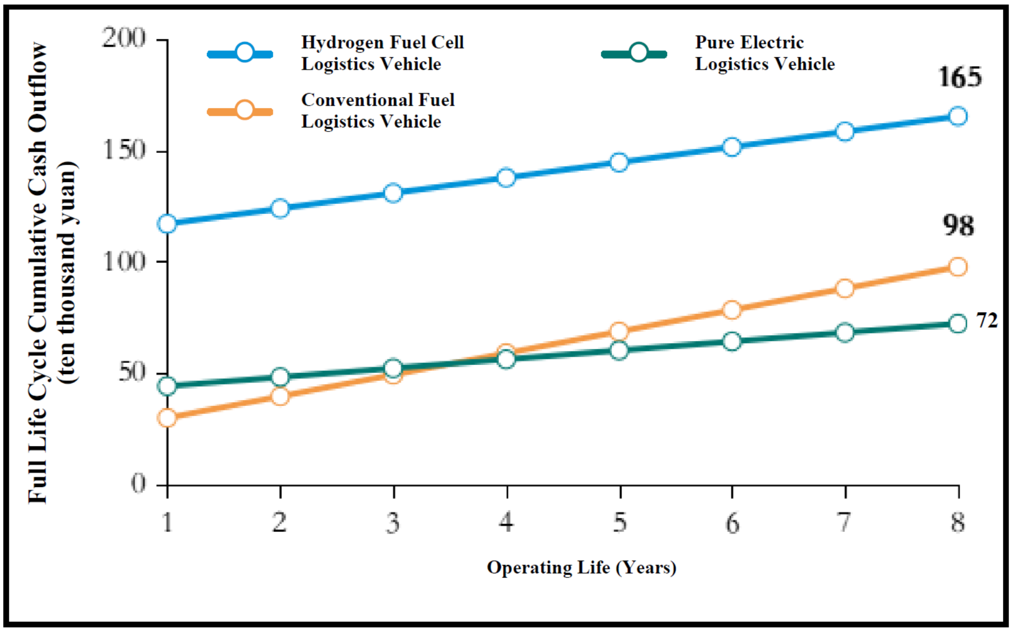
According to the model's measurement, without considering subsidies, the current annual operating cost of hydrogen fuel cell logistics vehicles is 199,700 yuan. This cost is significantly higher than that of conventional fuel logistics vehicles at 120,800 yuan per year and pure electric logistics vehicles at 87,600 yuan per year. The primary reason for the high operating cost of hydrogen fuel cell logistics vehicles is the elevated selling price of unsubsidized vehicles compared to conventional fuel logistics vehicles and pure electric logistics vehicles. Additionally, while operation and maintenance costs are lower than those of conventional fuel logistics vehicles, they are still higher than those of pure electric logistics vehicles. In comparison, although pure electric logistics vehicles have a higher initial acquisition cost, their lower operation and maintenance costs lead to lower cumulative cash flow expenditure in the fourth year of operation compared to conventional fuel logistics vehicles. This economic advantage continues to grow year by year, providing an inherent driving force for the transition to pure electric logistics vehicles. Therefore, the core factor enabling the application of hydrogen fuel cell logistics vehicles is the reduction of acquisition costs (assuming constant profit margins, tied to manufacturing costs) and fuel costs (linked to hydrogen consumption per 100 km and hydrogen price) through technological progress and industrial scaling (refer to "Fig. A.1.2.1 Comparison of Logistics Vehicle Operating Costs under Different Technical Strategies" and "Fig. A.1.2.2 Comparison of Logistics Vehicle Operating Costs under Different Technical Routes" for more details).

Fig. A.1.2.1 Comparison of Logistics Vehicle Operating Costs under Different Technology Routes



Items	Unit	Hydrogen Fuel Cell Logistics Vehicle	Conventional Fuel Logistic Vehicle	Pure Electric Logistics Vehicle
Fixed Cost				
Acquisition Cost	**Ten-thousand Yuan/Year**	**110**	**20**	**40**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	110	20	40
Annual Depreciation		**13.06**	**2.38**	**4.75**
Years of Depreciation	Year	8	8	8
Residual Value Rate	%	5%	5%	5%
Variable Cost				
Fuel Cost	**Ten-thousand Yuan/Year**	**4.41**	**7.20**	**1.51**
Energy Consumption Per 100km	kg, L, kWh	3	20	50
Energy Price	Yuan/(kg, L, kWh)	35	8	0.67
Daily Mileage	kilometer	150	150	150
Annual Operating Days	Day	300	300	300
Vehicle Maintenance Cost	**Ten-thousand Yuan/Year**	**1.5**	**1.5**	**1.5**
Other Cost	**Ten-thousand Yuan/Year**	**1.0**	**1.0**	**1.0**
Annual Operation and Maintenance Cost	**Ten-thousand Yuan/Year**	**6.91**	**9.70**	**4.01**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**19.97**	**12.08**	**8.76**

Fig. A.1.2.2 Comparison of Full Life Cycle Cumulative Cash Outflows of Logistics Vehicles under Different Technology Routes



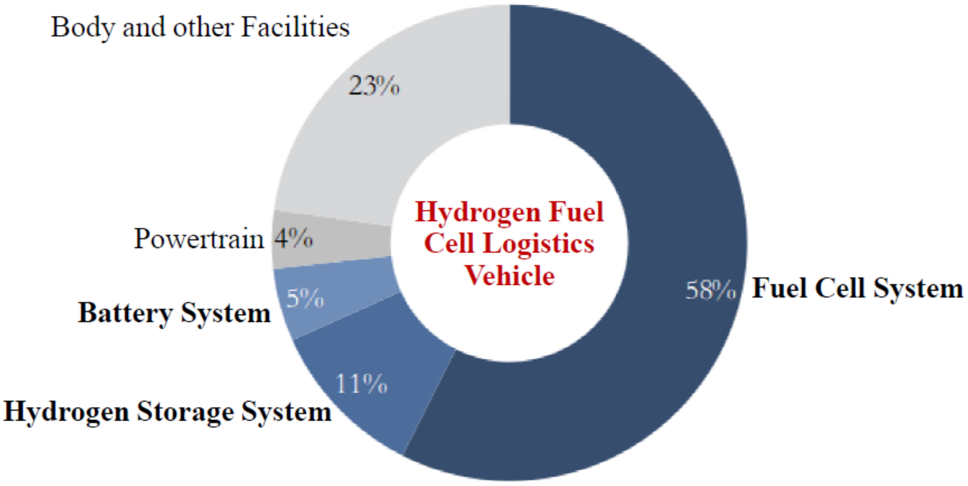
2) Operating Cost Reduction Model

2.1) Key Assumptions

The manufacturing cost of hydrogen fuel cell logistics vehicles is primarily driven by the cost of upstream components. The core components of hydrogen fuel cell logistics vehicles include the fuel cell system (58% of the cost), hydrogen storage system (11%), and battery system (5%). These components are still in the early stages of industrial research and development, presenting significant opportunities for future cost reduction. The drive system (4%) and the body and other facilities (23%) are more mature technologies and have been adapted from conventional fuel logistics vehicles. (Refer to Fig. A.1.2.3 for the cost structure of a 9-ton hydrogen fuel cell logistics vehicle.) The operation and maintenance costs are primarily determined by the fuel cost, which is directly related to hydrogen consumption per 100 km and the price of hydrogen refueling (refer to 5.3 Analysis of Hydrogen Industry Costs and Cost Reduction Model" for more information).

The key assumptions of the cost-reduction model for hydrogen fuel cell logistics vehicles can be found in the chapter on hydrogen fuel cell heavy-duty trucks. These assumptions apply to all scenarios involving hydrogen fuel cell vehicles.

Fig. A.1.2.3 Cost Structure of a 9-ton Hydrogen Fuel Cell Logistics Vehicle



2.2) Data Analysis

Without considering the cost-reduction paths of conventional fuel logistics vehicles and pure electric logistics vehicles, the projected operating cost of hydrogen fuel cell buses in 2030 is 102,500 yuan per year. This cost remains higher than the current operating costs of conventional fuel logistics vehicles at 120,800 yuan per year and pure electric logistics vehicles at 87,600 yuan per year. The main reason for the higher operating cost of hydrogen fuel cell logistics vehicles in 2030 is attributed to their vehicle selling price, which is projected to be 490,000 yuan. This selling price is still higher compared to the current selling prices of conventional fuel logistics vehicles (200,000 yuan) and pure electric logistics vehicles (400,000 yuan). However, the operations and maintenance (O&M) cost of hydrogen fuel cell logistics vehicles in 2030 is estimated to be only 44,800 yuan per year, which is significantly lower than the current O&M cost of conventional fuel logistics vehicles (97,000 yuan/year) and comparable to that of pure electric logistics vehicles (40,100 yuan/year). In summary, when focusing solely on overall economic aspects, hydrogen fuel cell logistics vehicles are expected to have the internal motivation to compete with pure electric logistics vehicles, particularly in high energy consumption scenarios such as cold chain vehicles (refer to 6.2 GLP's Case" for more details). However, for the economic advantages to be fully realized, the manufacturing cost must be further reduced (refer to "Fig. A.1.2.4 & A.1.2.5 Hydrogen fuel cell Logistics Vehicle Operating Cost Reduction Calculation" for more details).

Fig. A.1.2.4 Hydrogen Fuel Cell Logistics Vehicle Operating Cost Reduction Calculation

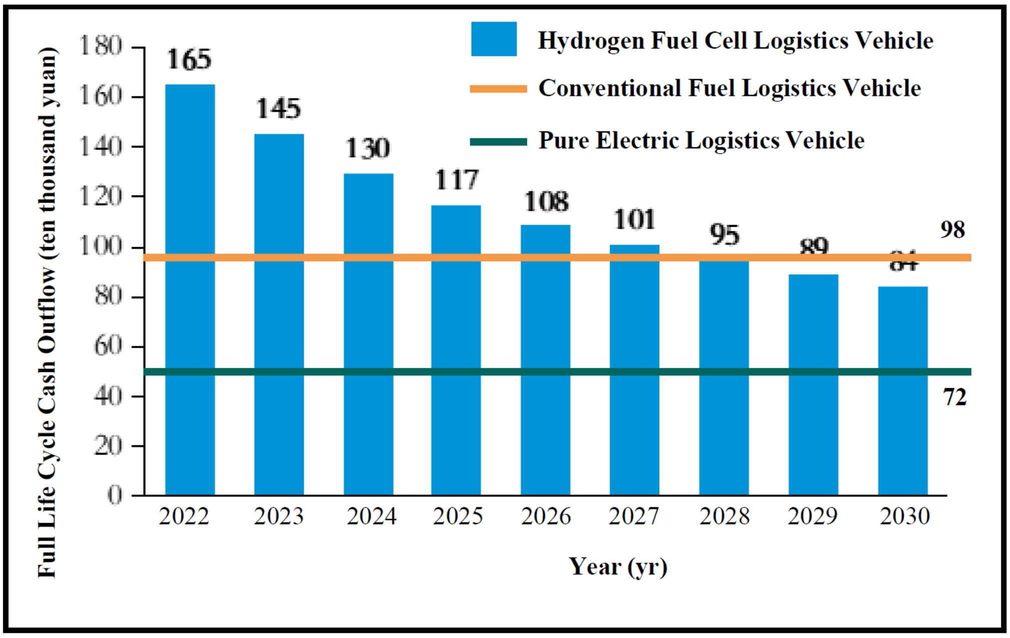


Fig. A.1.2.5 Hydrogen Fuel Cell Logistics Vehicle Operating Cost Reduction Calculation

Items	Unit	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fixed Cost										
Manufacturing Cost	**Ten thousand yuan**	**88**	**74**	**64**	**56**	**51**	**47**	**44**	**41**	**39**
Fuel Cell System	Ten thousand yuan	51	38	29	22	17	14	11	9	7
Average Annual Reduction	*%*		*25%*	*25%*	*25%*	*20%*	*20%*	*20%*	*20%*	*20%*
Hydrogen Storage System	Ten thousand yuan	10	9	8	8	7	7	7	6	6
Average Annual Reduction	*%*		*7%*	*7%*	*7%*	*5%*	*5%*	*5%*	*5%*	*5%*
Battery System	Ten thousand yuan	4	4	4	4	4	3	3	3	3
Average Annual Reduction	*%*		*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
Acquisition Cost	**Ten thousand yuan**	**110**	**93**	**80**	**70**	**64**	**59**	**55**	**51**	**49**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	110	93	80	70	64	59	55	51	49
Subsidy	Ten-thousand Yuan/vehicle	-	-	-	-	-	-	-	-	-
Subsidy Coefficient	-	-	-	-	-	-	-	-	-	-
Annual Depreciation	**Ten-thousand Yuan/Year**	**13.1**	**11.0**	**9.5**	**8.3**	**7.6**	**7.0**	**6.5**	**6.1**	**5.8**
Years of Depreciation	Year	8	8	8	8	8	8	8	8	8
Residual Value Rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Variable Cost										
Fuel Cost	**Ten-thousand Yuan/Year**	**4**	**4**	**4**	**3**	**3**	**3**	**2**	**2**	**2**
100km Hydrogen Consumption	kg/100km	2.8	2.7	2.6	2.6	2.5	2.4	2.3	2.3	2.2
Average Annual Reduction	*%*		*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*
Retail Price of Hydrogen	Yuan/kg	35	33	31	29	28	26	24	22	20
Daily Mileage	kilometer	150	150	150	150	150	150	150	150	150
Annual Operating Days	Day	300	300	300	300	300	300	300	300	300
Vehicle Maintenance Cost	**Ten-thousand Yuan/Year**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Other Cost	**Ten-thousand Yuan/Year**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Annual Operation And Maintenance Cost	**Ten-thousand Yuan/Year**	**7**	**7**	**6**	**6**	**6**	**5**	**5**	**5**	**4**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**20**	**18**	**16**	**14**	**13**	**12**	**11**	**11**	**10**

A.1.3 Hydrogen Fuel Cell Passenger Vehicles

1) Operating Cost Model

1.1) Key Assumptions

Due to the variety of passenger vehicles and their wide price range, the author uses the BMW iX5 hydrogen fuel cell passenger vehicle with a fuel cell system rated at 125 kW as an example to calculate the annual operating cost and potential cost-reduction path. This analysis is then compared with the BMW X5 conventional fuel passenger vehicle and the BMW iX5 pure electric passenger vehicle. The BMW X5/iX5 series is available in hydrogen fuel cell, conventional fuel, and pure electric versions. According to current public data, the driving performance and customer experience across these three models are generally similar, with the primary differences found in the powertrain. This enables a comprehensive and fair horizontal comparison between the models. To comprehensively compare the economics of each technology route, this model does not currently factor in subsidies. However, subsidies will be addressed later as a policy measure to guide cost-reduction efforts. The key assumptions of the model for the current time node are outlined below:

1) Purchase cost: Without subsidies, the price of a hydrogen fuel cell passenger vehicle is 1,030,000 yuan, while a conventional fuel passenger vehicle costs 620,000 yuan, and pure passenger vehicle costs 650,000 yuan.
2) Vehicle depreciation: The vehicles are depreciated over a 8-year operational lifespan, assuming a 5% residual value at the end of that period.

3） Fuel cost:

- Energy consumption per 100 km: Hydrogen fuel cell passenger vehicles consume 1.2 kg of hydrogen per 100 km, conventional fuel passenger vehicles consume 10 liters of oil per 100 km, and pure electric passenger vehicles consume 18 kWh of electricity per 100 km.
- Energy price: The cost of hydrogen is 35 yuan per kg, conventional fuel costs 8 yuan per liter, and electricity is priced at 0.67 yuan per kWh.
- Driving range: 50 km per day, 365 days of operation per year.

4） Vehicle maintenance fee: All 15,000 yuan/year.

5） Other costs: 0.5 million yuan/year for all. Furthermore, the purchase contract includes a 8-year full life-cycle warranty, with no additional cost for maintenance.

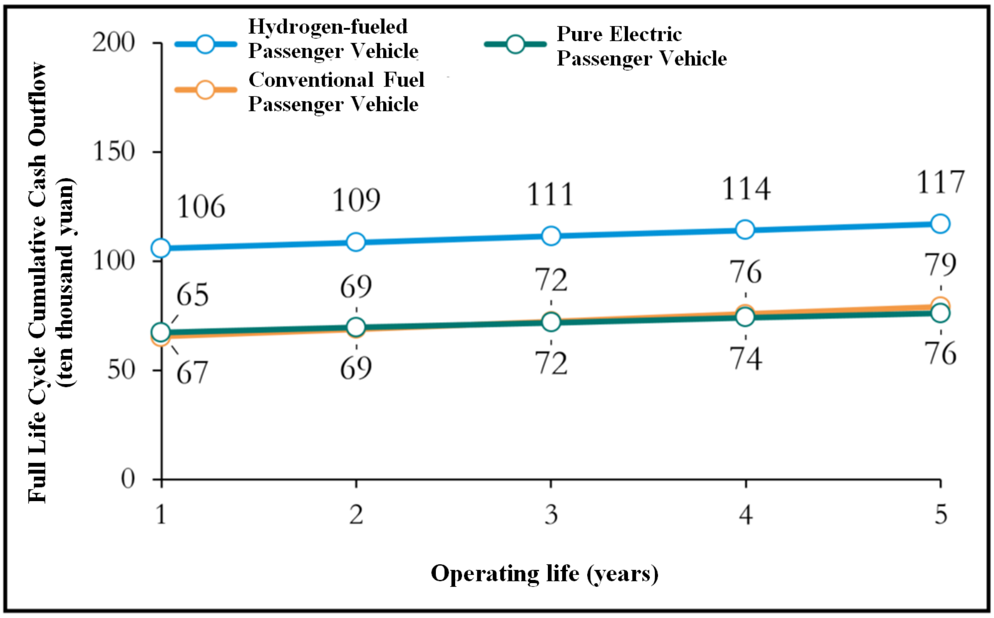
1.2) Data Analysis

According to the model's measurement, without considering subsidies, the current annual operating cost of hydrogen fuel cell passenger vehicles is 149,900 yuan. This cost is significantly higher than that of conventional fuel passenger vehicles at 107,600 yuan per year and pure electric passenger vehicles at 99,400 yuan per year. The primary reason for this is that the price of unsubsidized vehicles is much higher than that of conventional fuel passenger vehicles and pure electric passenger vehicles. Additionally, while operation and maintenance costs are lower than conventional fuel passenger vehicles, they are higher than pure electric passenger vehicles. In comparison, although pure electric passenger vehicles have a higher initial purchase cost, their lower operation and maintenance costs result in cumulative cash flow expenditure equaling that of conventional fuel passenger vehicles by the second year of operation. After that point, the economic advantage of pure electric vehicles expands year by year, providing an internal incentive for a transition to electric vehicles. Therefore, the core factor enabling the application of hydrogen fuel cell passenger vehicles is the reduction of acquisition costs (assuming constant profit margins, tied to manufacturing costs) and fuel costs (linked to hydrogen consumption per 100 km and hydrogen price) through technological progress and industrial scaling. (Refer to "Fig. A.1.3.1 Comparison of Operating Costs of Passenger Vehicles under Different Technology Routes" and "Fig. A.1.3.2 Comparison of Full Life Cycle Cumulative Cash Outflows of Passenger Vehicles under Different Technology Routes" for more details).

Fig. A.1.3.1 Comparison of Operating Costs of Passenger Vehicles under Different Technology Routes

Items	Unit	Hydrogen Fuel Cell Passenger Vehicle	Conventional Fuel Passenger Vehicle	Pure Electric Passenger Vehicle
Fixed Cost				
Acquisition Cost	**Ten-thousand Yuan/Year**	**103**	**62**	**65**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	103	62	65
Annual Depreciation		**12.23**	**7.36**	**7.72**
Years of Depreciation	Year	8	8	8
Residual Value Rate	%	5%	5%	5%
Variable Cost				
Fuel Cost	**Ten-thousand Yuan/Year**	**0.76**	**1.40**	**0.22**
Energy Consumption Per 100km	kg, L, kWh	1.2	10	18
Energy Price	Yuan/(kg, L, kWh)	35	8	0.67
Daily Mileage	kilometer	50	50	50
Annual Operating Days	Day	365	365	365
Vehicle Maintenance Cost	**Ten-thousand Yuan/Year**	**1.5**	**1.5**	**1.5**
Other Cost	**Ten-thousand Yuan/Year**	**0.5**	**0.5**	**0.5**
Annual Operation and Maintenance Cost	**Ten-thousand Yuan/Year**	**2.76**	**3.40**	**2.22**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**14.99**	**10.76**	**9.94**

Fig. A.1.3.2 Comparison of Full Life Cycle Cumulative Cash Outflows of Passenger Vehicles under Different Technology Routes



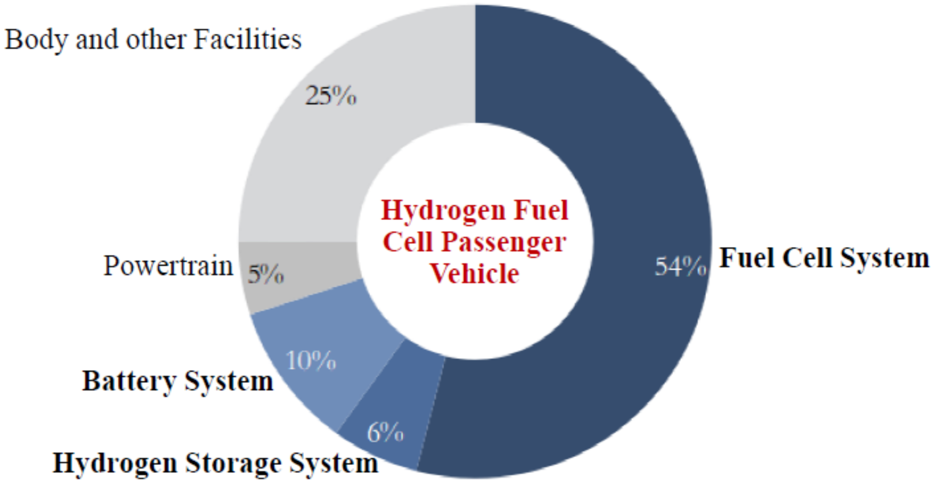
2) Operating Cost Reduction Model

2.1) Key Assumptions

The manufacturing cost of hydrogen fuel cell passenger vehicles is primarily driven by the cost of upstream components. The core components of hydrogen fuel cell passenger vehicles include the fuel cell system (54% of the cost), hydrogen storage system (6%), and battery system (10%). These components are still in the early stages of industrial research and development, presenting significant opportunities for future cost reduction. The drive system (5%) and the body and other facilities (25%) are more mature technologies and have been adapted from conventional fuel logistics vehicles (refer to "Fig. A.1.3.3 Cost Structure of BMW iX5 Hydrogen fuel cell Passenger Vehicle" for more details). The operation and maintenance costs are primarily determined by the fuel cost, which is directly related to hydrogen consumption per 100 km and the price of hydrogen refueling (refer to 5.3 Analysis of Hydrogen Industry Costs and Cost Reduction Model" for more information).

The key assumptions of the cost-reduction model for hydrogen fuel cell passenger vehicles can be found in the chapter on hydrogen fuel cell heavy-duty trucks. These assumptions apply to all scenarios involving hydrogen fuel cell vehicles.

Fig. A.1.3.3 Cost Structure of the BMW iX5 Hydrogen fuel cell Passenger Vehicle



2.2) Data Analysis

Without considering the cost-reduction paths of conventional fuel passenger vehicles and pure electric passenger vehicles, the projected operating cost of hydrogen fuel cell passenger vehicles in 2030 is 81,900 yuan per year. This cost remains higher than the current operating costs of conventional fuel logistics vehicles at 107,600 yuan per year and pure electric logistics vehicles at 99,400 yuan per year. The main reason for the higher operating cost of hydrogen fuel cell passenger vehicles in 2030 is attributed to their vehicle selling price, which is projected to be 490,000 yuan. This selling price is still higher compared to the current selling prices of conventional fuel passenger vehicles (620,000 yuan) and pure electric logistics vehicles (650,000 yuan). The operations and maintenance (O&M) cost of hydrogen fuel cell passenger vehicles in 2030 is estimated to be only 23,400 yuan/year, which is lower than the current O&M cost of conventional fuel passenger vehicles (34,000 yuan/year) and roughly equivalent to that of pure electric passenger vehicles (22,200 yuan/year). In summary, considering only the final economic factors, hydrogen fuel cell passenger vehicles are expected to have an inherent motivation to compete with pure electric passenger vehicles. However, further reduction in manufacturing costs is necessary to unlock their economic advantages (refer to "Fig. A.1.3.4 & Fig. A.1.3.5 Hydrogen fuel cell Passenger Vehicle Operating cost Reduction Calculation" for more details).

Based on the modeling described above, it will require a minimum of 3 years for the entire life cycle cash flow of hydrogen fuel cell passenger vehicles to match that of pure electric passenger vehicles. Referring to data from the China Association of Passenger Vehicle Manufacturers (CAPVM), the current adoption rate of electric passenger vehicles (including pure electric and hybrid) in China has surpassed 40%, with expectations for continued growth in the future. The author asserts that electric passenger vehicles enjoy a distinct first-mover advantage, leveraging initial national and local resource subsidies along with established infrastructure advantages such as charging stations and power-exchange facilities. Although hydrogen fuel cell passenger vehicles theoretically offer advantages in end-game economics, their late entry into the market, combined with the decentralized nature of passenger vehicle usage and the need for flexible hydrogen refueling, present challenges. The development and implementation of actual infrastructure, such as hydrogen refueling stations and hydrogen storage and transportation systems, are slower and require substantial upfront investments. The potential for large-scale commercialization of hydrogen fuel cell passenger vehicles remains highly uncertain until infrastructure challenges are effectively addressed.[29, 30]

Fig. A.1.3.4 Hydrogen fuel cell Passenger Vehicle Operating Cost Reduction Calculation

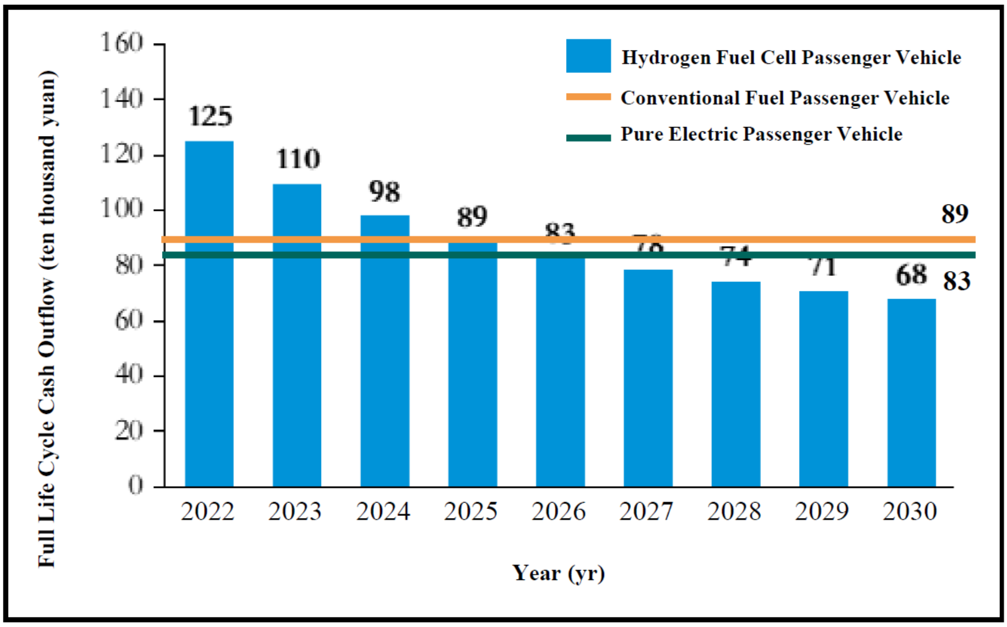


Fig. A.1.3.5 Hydrogen Fuel Cell Passenger Vehicle Operating Cost Reduction Calculation

Items	Unit	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fixed Cost										
Manufacturing Cost	**Ten thousand yuan**	**82**	**71**	**61**	**55**	**50**	**47**	**44**	**41**	**39**
Fuel Cell System	Ten thousand yuan	44	33	25	19	15	12	10	8	6
Average Annual Reduction	*%*		*25%*	*25%*	*25%*	*20%*	*20%*	*20%*	*20%*	*20%*
Hydrogen Storage System	Ten thousand yuan	5	5	4	4	4	4	3	3	3
Average Annual Reduction	*%*		*7%*	*7%*	*7%*	*5%*	*5%*	*5%*	*5%*	*5%*
Battery System	Ten thousand yuan	8	8	7	7	7	6	6	6	5
Average Annual Reduction	*%*		*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
Acquisition Cost	**Ten thousand yuan**	**103**	**88**	**77**	**68**	**63**	**58**	**55**	**52**	**49**
Vehicle Selling Price	Ten-thousand Yuan/vehicle	103	88	77	68	63	58	55	52	49
Subsidy	Ten-thousand Yuan/vehicle	-	-	-	-	-	-	-	-	-
Subsidy Coefficient	-	-	-	-	-	-	-	-	-	-
Annual Depreciation	**Ten-thousand Yuan/Year**	**12.2**	**10.5**	**9.1**	**8.1**	**7.5**	**6.9**	**6.5**	**6.1**	**5.9**
Years of Depreciation	Year	8	8	8	8	8	8	8	8	8
Residual Value Rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Variable Cost										
Fuel Cost	**Ten-thousand Yuan/Year**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**
100km Hydrogen Consumption	kg/100km	1.2	1.2	1.1	1.1	1.1	1.0	1.0	1.0	0.9
Average Annual Reduction	*%*		*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*	*3%*
Retail Price of Hydrogen	Yuan/kg	35	33	31	29	28	26	24	22	20
Daily Mileage	kilometer	50	50	50	50	50	50	50	50	50
Annual Operating Days	Day	365	365	365	365	365	365	365	365	365
Vehicle Maintenance Cost	**Ten-thousand Yuan/Year**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Other Cost	**Ten-thousand Yuan/Year**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Annual Operation and Maintenance Cost	**Ten-thousand Yuan/Year**	**3**	**3**	**3**	**3**	**3**	**2**	**2**	**2**	**2**
Annual Operating Cost	**Ten-thousand Yuan/Year**	**15**	**13**	**12**	**11**	**10**	**9**	**9**	**9**	**8**

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