

Article

Accelerating Towards Sustainability: Policy and Technology Dynamic Assessments in China's Road Transport Sector

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Abstract: This study examines the policy and technological dynamics shaping China's road transport sector's transition to low-carbon sustainability, focusing on battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (HFCEVs). As the world's second-largest carbon emitter, China faces significant challenges in reducing its fossil fuel dependency in road transport, which accounts for diverse emissions and energy security risks. The present work, using a dual tech multi-level perspective (DTMLP) framework integrating multi-level perspective (MLP) and an advocacy coalition framework (ACF), analyzes the interplay of landscape pressures (global carbon constraints), regime dynamics (policy–market interactions), and niche innovations (BEV/FCEV competition). The results reveal BEVs' dominance in light-duty markets, achieving remarkable operational emission reductions but facing lifecycle carbon lock-ins from battery production and coal-dependent power grids. HFCEVs demonstrate potential for heavy-duty decarbonization but struggle with gray hydrogen reliance and infrastructure gaps. Policy evolution highlights shifting governance from subsidies to market-driven mechanisms, alongside regional disparities in implementation. This study proposes a three-phase roadmap: structural optimization (2025–2030), technological adaptation (2030–2045), and hydrogen–electric system integration (post-2045), emphasizing material innovation, renewable energy alignment, and multi-level governance. Our findings underscore the necessity of coordinated policy–technology synergies, grid decarbonization, and circular economy strategies, to overcome institutional inertia and achieve China's 'Dual Carbon' targets. This work provides actionable insights for global sustainable transport transitions amid competing technological pathways and geopolitical resource constraints.

Keywords: China; low-carbon transportation; multilevel perspective analysis; battery vehicles; hydrogen fuel cell vehicles; policy coordination path



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1. Introduction

As the world's second-largest contributor to carbon emissions, the transport sector poses a significant challenge within the realm of global climate change governance [1], and this is particularly pertinent for road transport, which heavily relies on fossil fuels, encompasses a diverse range of sources, and caters to a vast user base [2–4]. The United

Nations Sustainable Development Goal 11.2 framework promotes electric, non-motorized, and renewable fuel transportation systems, urging countries to enhance their National Determined Contributions (NDCs) to strengthen environmental policy frameworks [5], particularly regarding efficient incentives and subsidies for the new energy vehicles (NEVs) sector.

As the country has become the largest market for NEVs globally, China's development trajectory for road transport is significant. In 2023, NEVs, including fuel cell electric vehicles (FCEVs), hybrid electric vehicles (HEVs), and battery electric vehicles (BEVs), achieved a market penetration rate of 31.6%, resulting in an emission reduction of 80 million tons [6]. However, this growth falls short of the ambitious target of reaching 90% penetration by 2035. The decline in financial subsidies, reflected in an decrease in the average yearly increase speed of patent filings from 2001 to 2018, highlights a growing conflict between institutional path dependence and a lack of incentives for technological innovation [7]. Several systemic barriers, such as dependence on imported core materials [8], the imbalance between supply and demand for charging infrastructure [9], the high cost associated with complete life cycle emission reduction [10], and the elevated costs of toxic exhaust gas emissions [11], reveal the limitations of a solely policy-driven approach. To address the current issues, a paradigm shift from 'Policy Blood Transfusion' to 'Technology Blood Creation' is essential for the sustainable growth of the NEV industry [12].

The transition to sustainable low-carbon technologies is generally categorized into three essential stages: invention, innovation, and diffusion. This process, from an examination of the practices employed by various countries, encounters various market, systemic, and institutional failures; consequently, this necessitates a range of policy interventions and adjustments to address these challenges effectively. Recently, China has implemented a series of policies, at both regional and national levels, to promote the sustainable development of NEVs. These initiatives include technology-driven strategies focusing on hybrid technologies, high-performance transmissions, electronics, and lightweight materials. Research has shown that effectively integrating relevant technologies with specific policy tools employed by the government is crucial for advancing or impeding this transition [13]. To explore the linkages between policy and technological change, various frameworks have been developed for policy portfolio analysis, of which some concern feedback loops in vertical policy coordination at the regional and national levels [13], some focus on the consistency of elements (like policy processes and policy characteristics) and the coherence of policy processes in policy portfolios [14], and some identify the most promising electric vehicle technologies by examining the market and technology attributes of technologies [15]. However, prior studies have primarily concentrated on a single model or governance level [16] or have assessed the effectiveness of individual low-carbon technologies in reducing emissions [17,18], without considering the coherence and intrinsic linkages among diverse combinations of policies, markets, and technologies. These limitations hinder existing theories in adequately explaining the complex evolution of China's NEV industry, which is marked by 'declining policy incentives, sluggish market response, and rapid technology iteration'. In the context of advancing the 'Dual-Carbon' target, the government, industry, and everyday users face significant dilemmas, opportunities, and challenges as they navigate the low-carbon transformation of the road transportation sector.

This study innovatively develops a dual tech multi-level perspective (DTMLP) framework focused on BEVs and FCEVs, aiming to transcend the limitations of linear thinking inherent in traditional analysis. By examining the three-dimensional, synergistic evolution of landscape (global carbon constraints and national strategies), regime (policy-market interaction), and niche (BEV/FCEV technology competition), the study reveals the dynamics of competition and complementarity between these dual technology pathways.

Consequently, it proposes a three-phase roadmap for the low-carbon transformation of road transport in China, reported in the present article using the following organizational structure: Section 1 introduces the subject matter; Section 2 reviews the literature on NEV technologies, theoretical and analytical methodologies, as well as the development of low-carbon road transport policies in China; Section 3 provides a detailed explanation of research techniques, including the multi-level perspective (MLP); Sections 4–6 present the findings of the studies alongside a comprehensive summary of the literature review; Section 7 proposes a three-phase roadmap for China's road transport sector; and Section 8 summarizes the entire text and outlines its policy implications. Figure 1 illustrates the specific logic discussed throughout the paper.

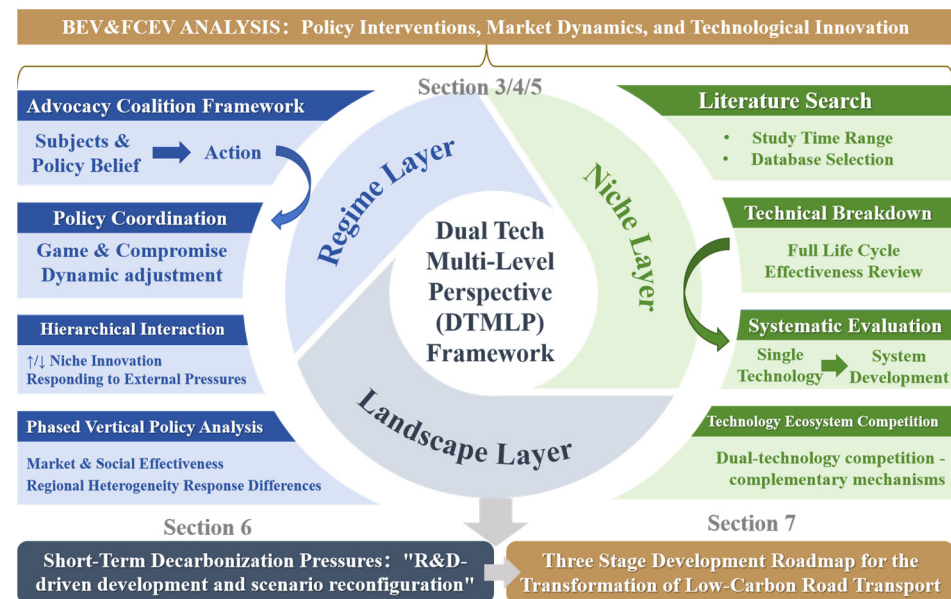


Figure 1. Dual tech multi-level perspective (DTMLP) framework and the organizational structure of the present article.

2. Evolution of Governance Frameworks and Innovative Practices in China's Low-Carbon Transition: A Literature Review on Multi-Level Integration and Regional Responses

2.1. Multi-Path Technological Development and Synergistic Potential of NEVs: Current Challenges and Theoretical Framework

As a pivotal industry in addressing the challenges of energy security and climate governance, NEVs are reshaping the traditional transportation energy paradigm through innovations in power systems, including hybrid, pure electric, and fuel cell technologies, whose evolution can be characterized by multi-path approaches, with four primary research dimensions:

- (i) Technology trajectory analysis, which employs the main path analysis method to trace the developmental trajectory of NEVs and to investigate the core research themes associated with them [19];
- (ii) Policy–technology interactions, which concern the dynamic inter-relationships and knowledge trajectories between fuel cell technologies and the supporting technology policies [18,20];
- (iii) Competitive posture forecasting, which leverages patent information for tracking technological advancements and forecasting, aiming to identify development pathways and analyze the competitive stance of critical technologies [21];

- (iv) Life cycle assessment (LCA), which comprehensively evaluates the external costs of NEVs [22].

According to related studies, BEVs and FCEVs represent the cornerstone technologies of the NEV landscape within current and future sustainable transportation frameworks, exhibiting a diverse development trend globally and in China. Continuous technological advancements worldwide, such as improvements in lithium battery energy density [23], are propelling the expansion of the BEV market. In 2024, global BEV sales were projected to increase by 24.4% [24], with Europe's penetration rate surpassing 30%. Meanwhile, FCEVs continue to leverage their endurance advantages in the heavy-load sector [25], though they still grapple with the significant costs associated with hydrogen production [26]. Additionally, there are notable regional strategic variances, with developed countries increasingly focusing on the comprehensive establishment of hydrogen societies.

In China, both BEVs and FCEVs are rapidly advancing, driven by robust policy frameworks, innovative policy instruments, and enhanced institution design, including medium- and long-term planning for the hydrogen industry, aimed at achieving technology localization. However, challenges persist, including limitations in pilot projects, inadequate coverage, and delays in industrialization [26]. Existing research has tended to concentrate on individual key technologies or the broader new energy industry, leaving the synergistic potential between these two technological dimensions insufficiently explored. There is a pressing need to develop a systematic theoretical framework that addresses this gap.

2.2. Theoretical Limitations in the Low-Carbon Energy Transition and Differential Responses of Symbiotic Technologies Under the Multi-Level Perspective

The transition to low-carbon energy within the energy-using sector has been analyzed through various theoretical frameworks. For instance, the diffusion of innovation theory highlights the importance of regional technology sharing, where technological advancements are posited as the main drivers of change [27]; the technology acceptance model; and the techno-economic paradigm [28]. However, it struggles to explain the observed decline in patent filings yearly increase speed within the market for NEVs, even as battery capacity density continues to rise [7]. On the other hand, institutional theory addresses the concept of institutional inertia and underscores the influence of factors such as policies, laws, and social norms on the low-carbon transition [29]. However, it fails to address the limitations of existing national–regional vertical policies. Systems theory [30] emphasizes the feedback mechanisms and synergies among internal components, to optimize regional economic resources. However, the transmission of cross-border pressure has not been fully integrated into this analytical approach.

Before new technologies can achieve widespread adoption and effect significant economic changes, modifying the institutional, legal, and social norms currently supporting outdated technologies is essential. In this context, Geels F.W. [31] introduced the Multi-Level Perspective (MLP) framework to analyze technological development transitions within social systems. This framework is grounded in socio-technical systems, acknowledging the multifaceted nature of participation in spatial and temporal transformations and the capabilities of the various actors involved. In the MLP framework, socio-technical transformation is described as the process through which incumbent actors redirect innovative activities and developments [32], which can be analyzed across three levels [33]:

- (i) Landscape level, which represents the macro level, encompassing various exogenous factors and the broader external environment that facilitates interactions among institutional and niche-level players;
- (ii) Regime level, which is made up of stakeholders, including policy regulations and social norms, as well as utility infrastructure and practices;

(iii) Niche level, which is the micro level of the multi-level perspective (MLP) analytical framework, where new technologies are introduced.

The MLP has been extensively applied in systematic evaluations of transformational shifts, such as those involving BEVs [34] and smart grids [35]. Significant competition was observed among industrial policies, user behaviors, and social contexts when these technologies were integrated in [36]. Meanwhile, the MLP analysis framework and/or other theoretical examinations of the NEV industry within the road transportation sector have typically adopted a singular perspective. This approach overlooks the differentiated response mechanisms of ‘symbiotic technologies’ under the same landscape pressure, such as the potential benefit from the synergistic opportunities presented by intelligent grid advancements [37] or the possible impacts of the green hydrogen economy [38].

2.3. Multi-Level Governance Framework for China’s Low-Carbon Transportation Transition: Policy Evolution and Regional Innovation Dynamics

2.3.1. Evolution of China’s Low-Carbon Transportation Policy Framework and Central–Local Governance Challenges: From the ‘1 + N’ System to Green Transition Practices

Upon its commitment to sustainable development and international cooperation, China’s approach to enhancing low-carbon emission reduction policies (as listed in Table 1) in the transportation sector has progressively evolved throughout various stages of economic and social development.

Table 1. Energy conservation and emission reduction policies in China’s road transportation sector (up to October 2024).

Time	Policy Act	Concrete Concept
2006 (March)	Outline of 11th Five-Year Plan for National Economic and Social Development of the People’s Republic of China	Urgent political action on climate change is essential, emphasizing oil conservation, while pursuing alternative fuels like coal liquefaction and alcohol ether. Prioritize fuel-saving strategies vital for energy conservation in power and transportation, placing these initiatives at the forefront to effectively combat climate change.
2008 (January)	Several Opinions on Accelerating the Development of the Modern Transportation Industry	The government will prioritize energy conservation and emission reduction through initiatives like clean transportation, strict energy standards, closing energy-intensive facilities, and promoting alternative energy sources. These actions aim to protect the environment and fulfil public demand for responsible energy policies.
2008 (June)	Setting Energy Conservation and Emission Reduction Targets for the Transport Sector During the 11th Five-Year Plan Period	By 2010 and 2020, aim for a 5% and 16% reduction in energy consumption per unit of transport volume for trucks. This shift is crucial for enhancing energy conservation in transportation and fostering a progressive energy-saving innovation system aligned with our commitment to a sustainable future.
2009 (January)	Notice on Carrying Out Demonstration and Pilot Promotion of Energy-Saving and New Energy Vehicles	Launch a pilot program for energy-saving vehicles in cities like Beijing and Shanghai, with fiscal incentives to boost public service adoption, especially buses. This initiative aims to enhance urban transportation sustainability and demonstrate the government’s commitment to a greener future through collaboration for environmental goals.

Table 1. Cont.

Time	Policy Act	Concrete Concept
2011 (June)	Outline of 12th Five-Year Plan for National Economic and Social Development of the People's Republic of China	Advocate for low-carbon tech R&D to combat climate change. Urge stricter emission controls in key sectors. Support energy-saving technology and trials. Call for better regulations on energy conservation. Promote certification of energy-saving products for quality and advocate for mandatory government procurement to ensure sustainability.
2016 (March)	Outline of 13th Five-Year Plan for National Economic and Social Development of the People's Republic of China	Encourage support for low-carbon development through smart transportation and eco-friendly vehicles. Advocate for improved transportation and energy policies, promote low-carbon technologies, push for stricter emissions regulations in key industries, and support a unified carbon trading market nationally and internationally.
2018 (July)	Notice on Carrying Out Pilot Projects for the Recycling and Utilization of Power Batteries of New Energy Vehicles	Advocate recycling new energy vehicle batteries by establishing a service network. Enhance initiatives with consumer incentives like repurchase programs and battery exchanges. This tackles environmental concerns and promotes sustainability, aligning with our commitment to a greener future.
2019 (April)	Guidelines on Accelerating the Transformation and Upgrading of the Road Freight Transport Industry to Promote High-Quality Development	Phase out old diesel trucks and promote new energy vehicles for a greener future. Support the modernization of logistics for sustainability. Encourage the use of new energy vehicles and ships to minimize environmental impacts. Implement differentiated tolls on expressways to incentivize low-emission transport and foster sustainable logistics solutions.
2020 (December)	Energy in China's New Era	Advance hydrogen energy development by improving technologies for green hydrogen production, storage, transportation, and applications. This initiative will also support growth in hydrogen fuel cell vehicles, reinforcing our commitment to sustainable energy as a national priority.
2021 (February)	Outline of the National Comprehensive Transportation Network Plan	Advocate for a low-carbon development agenda, stressing the urgent need to enhance transport infrastructure. Promote new energy technologies and strong pollution monitoring systems. Focus on low-carbon transport initiatives as a key strategy for combating climate change and driving sustainable growth.
2021 (October)	Guiding Document on the Country's Work to Achieve Carbon Peaking and Carbon Neutrality Goals under the New Development Philosophy	Advocate for the political imperative of fostering green initiatives and the sustainable transformation of both urban and rural development. Push for low-carbon transportation solutions, endorse the adoption of new energy vehicles, and call for strategic enhancements in transportation infrastructure. Furthermore, support legislative measures aimed at advancing electrification initiatives.
2021 (October)	The 14th Five-Year Plan for Green Transportation Development	Build a low-carbon transport system to tackle climate change. Foster green transport innovations and promote sustainable energy sources. Inspire citizens to adopt eco-friendly travel practices and enhance our transport infrastructure. Collective action and policy support are crucial for success.

Table 1. Cont.

Time	Policy Act	Concrete Concept
2021 (November)	Opinions on Further Strengthening the Battle to Prevent and Control Pollution	Continue combating diesel truck pollution, a major issue for our communities. The government will enhance campaigns for clean diesel vehicles, phasing out those below national emission standards and promoting hydrogen fuel cell and clean energy options. Together, we can create a healthier future and ensure accountability to these standards.
2021 (December)	Work Plan for Promoting Multimodal Transportation Development and Optimizing Transportation Structure (2021–2025)	Advocate for shifting bulk materials to rail and waterways, highlighting combined transport benefits for iron and water. Exploring a coordinated rail and water system for bulk solid waste is vital. Integrating port resources optimizes transportation infrastructure and supports economic and environmental goals.
2023 (April)	Five-Year Action Plan for Accelerating the Construction of a Strong Transportation Country (2023–2027)	Promote a transformative agenda for bulk material transport that prioritizes sustainability, boosts eco-friendly freight capacity, and strengthens pollution prevention. Support low-carbon, diverse transportation energy strategies that align with green policies to combat climate change.
2024 (October)	Guidance on Promoting Renewable Energy Replacement	Enhance commitment to replace fossil fuels with renewables; promote their integration in key sectors like industry, transportation, and construction; and support policies for a low-carbon transition. Additionally, encourage innovative business models like digital energy solutions and virtual power plants for a sustainable future.

Since 2006, the Chinese government has demonstrated a significant commitment to addressing climate change through energy conservation and adopting alternative fuels. Launching the 13th Five-Year Plan (2016–2020) marked the beginning of a new phase in this effort. The government has shifted its focus toward facilitating a comprehensive integration of advanced intelligent technologies within energy systems and the transportation sector. Since 2020, the central government has established a ‘1 + N’ carbon peak and carbon neutrality policy framework [39], where ‘1’ represents the primary commitment to achieving a carbon peak and carbon neutrality, serving as a guiding principle for governmental initiatives, and ‘N’ encompasses specific implementation strategies tailored to various regions, sectors, and industries.

This framework has significantly emphasized the principles of green transportation and low-carbon transformation, indicating a paradigm shift in policies, from a focus on technology promotion to system transformation. Moreover, the government highlights the need for a comprehensive approach to the green and low-carbon transformation of road transportation. This involves diverse strategies, including policy guidance, technical support, market mechanisms, and infrastructure development, all aimed at fostering synergistic progress across various sectors and outlining a more coherent and coordinated future trajectory.

However, this transformation process poses a ‘national–local’ vertical governance dilemma. The planning gap between local systems and technology, which often requires an average of 12 administrative approvals for a single infrastructure project, hampers effective technological development and intensifies the disparity in regional technological advancement. As will be explored later, various degrees of deviation exist between local responses and national objectives, driven by regional economic and social heterogeneity.

2.3.2. Regional Differentiated Governance and Innovative Paradigms in Low-Carbon Transportation: Case Comparisons and Mechanism Analysis of Beijing, Shanghai, and Guangdong

Cities' developmental trajectories exhibit considerable variability, contingent upon their size. Consequently, the formulation of central economic, environmental, and climate policies necessitates the design of specific strategies congruent with each region's distinctive attributes. This process mandates a rigorous analysis of the underlying challenges and emphasizes the importance of effective implementation mechanisms to ensure policy efficacy. Reducing transportation emissions is essential in densely populated megacities [40], as they significantly impact public health and governance. However, urban advancements also offer models for enhancing energy efficiency and cutting emissions, bolstered by various pilot programs. This section will analyze relevant policies and explore an innovative differentiation system that addresses the current challenges of urban agglomerations.

Beijing, the capital of China, faces significant challenges with traffic congestion and elevated levels of air pollution. Since hosting the Olympics in 2008, Beijing has made strides in enhancing public transportation and promoting sustainable travel options. Various initiatives aimed at reducing vehicular pollution and supporting low-carbon transport have been introduced. The 14th Five-Year Plan for Transportation Development, launched in 2020, sought to modernize the system with green principles, addressing congestion to improve air quality. To incentivize public transit use, Beijing has introduced a program of carbon incentives that converts subway travel into personal carbon credits (1 credit equals 0.5 kg of CO_{2eq.}). These credits can be redeemed for discounts on charging or bus card recharges. Over one million residents have participated in this initiative, collectively reducing more than 400,000 tons of emissions.

Shanghai, as China's economic hub, boasts a dense and intricate multi-level transportation system. In the context of developing new energy vehicles, both the 12th and 13th Five-Year Plans emphasized the integration of solar energy into transportation infrastructure. This approach has evolved from setting initial goals to building essential charging facilities and promoting industrialization, positioning the region as a pilot area for advanced technology development. Since the inception of the 14th Five-Year Plan, Shanghai has shifted its focus towards achieving a green, low-carbon transformation and advancing intelligent transportation systems. Leveraging the benefits of a free trade zone, Shanghai has introduced a 'Green Electricity Certification' system, enabling companies to offset their charging carbon emissions by acquiring green certificates from the Zhangjiang photovoltaic (PV) power station.

Guangdong Province, China's largest province in terms of economic output, initiated a series of measures in 2007 to enhance energy conservation and reduce transportation emissions. The strategies embraced the promotion of public transportation and adoption of clean energy vehicles, while also proposing the gradual phase-out of high-emission vehicles. Throughout the 2010s, policy efforts increasingly centered on optimizing the transportation system, culminating in establishing more defined objectives in 2014 that focused on integrating various transport modalities to enhance energy efficiency and uphold environmental standards. During the implementation of the 13th Five-Year Plan, there was a notable shift towards refining the transportation structure and fostering a green transformation across the system, to facilitate sustainable transport development. Guangdong has developed a blockchain-based 'Carbon Lock' system to address the challenges of monitoring carbon emissions in cross-border logistics within the Guangdong–Hong Kong–Macao Greater Bay Area. This system enables real-time tracking of emissions data from diesel heavy-duty trucks and automates the deduction of carbon quotas for Guangdong, Hong Kong, and

Macao. This comprehensive approach reflects the province’s commitment to achieving a more sustainable and environmentally responsible transportation framework.

Table 2 briefly compares the innovation paradigms of low-carbon transportation governance in 2024 among Beijing, Shanghai, and Guangdong.

Table 2. Innovation paradigms of low-carbon transportation governance in megacities in 2024.

Megacity	Beijing (Administrative Center)	Shanghai (Economic Center)	Guangdong (Manufacturing Hub)
Problem Focus	Congestion-derived operational emissions	Port shipping and urban traffic superimposed pollution	Carbon leakage in cross-border logistics
Policy Instrument	AI signal optimization + tidal lanes	Bank power forced access + hydrogen energy heavy card priority pathway	‘Public service to iron’ subsidy + cross-border green electricity certification
Technical Adaptation	Low-temperature sodium battery bus pilot	Photovoltaic highway + V2G peak and valley electricity price	Methanol reforming for hydrogen production + LOHC storage and transportation
Collaborative Mechanism	Beijing–Tianjin–Hebei carbon market transportation plate	Agreement on the interconnection of charging facilities in the Yangtze River Delta	Hydrogen energy supply chain finance in the Guangdong–Hong Kong–Macao Bay Area

3. Research Methodology: Multi-Level Analysis and Data Collection Through an Integrated MLP-ACF Framework

The present study constructs a multi-dimensional analytical framework encompassing landscape, regime, and niche levels and based on the MLP theory, as listed in Table 3. The boundaries are operationalized at each level: the landscape level integrates exogenous drivers such as macro social-political dynamics (e.g., energy security imperatives and global climate governance agendas); the regime layer focuses on the ICE (internal combustion engine)-dominated technological system, with its inherent path dependencies (including technological rigidity, market structural inertia, consumer habits, and infrastructure effects); while the niche level captures multi-scalar innovation practices (e.g., localized pilot projects, early adopter cultivation, and policy–market co-evolution experiments). This research establishes a cross-level data triangulation mechanism to unravel the multidimensional interactions underpinning technological transition dynamics by systematically synthesizing policy documents, industry databases, and innovation case repositories.

While MLP theory emphasizes the meta-coordination of socio-technical institutions, it exhibits theoretical limitations in deconstructing the dynamic reconfiguration of actor networks. In contrast, the advocacy coalition framework (ACF) functions as a policy analysis tool, concentrating on the interactions among multiple advocacy coalitions (interest groups) within policy arenas and elucidating mechanisms of policy change through a diachronic analysis of the evolution of belief systems among coalition members. The core proposition of the ACF posits that actor collectives sharing congruent value orientations influence policy formulation and institutional restructuring through collective action strategies, thereby constructing stable policy subsystems. Recent scholarly efforts have advanced the integration of the MPL framework and the ACF, exemplified by Swiss energy transition research [30], which validated complementarity through institutional-level cross-scale coordination analysis. Building upon this foundation, the present study deconstructs the landscape of the NEV industry into multiple advocacy coalitions (each characterized by distinct objective functions and action strategies), necessitating systematic delineation of their structural components, belief systems, and strategic interaction patterns. Furthermore,

a policy subsystem analytical framework grounded in the ACF methodology is introduced at the regime level, establishing an explanatory paradigm for institution–actor co-evolution.

Table 3. The MLP analysis framework and data category design.

Analysis Hierarchy	Definition and Category	Data Sources
Landscape	Macro-social and technical environmental pressures (e.g., carbon neutral target, energy security)	– IPCC Report, IEA Global Energy Data – Macroeconomic indicators of the National Bureau of Statistics – China Energy Statistical Yearbook
Regime	Existing institutional structure and policy systems (such as central/local policy tools)	– White Paper of the Central Government (2006–2024) – Provincial policy document (Beijing, Shanghai, Guangdong) – Industry standard text
Niche	Technological innovation and experimentation (e.g., BEVs/FCEVs technology breakthrough)	– Related technology literature – Local government pilot report – Enterprise technology roadmap

To achieve a more comprehensive and accurate understanding of the specific policy formulations and practical applications of road traffic NEVs, both domestically and internationally, a strategy involving utilizing multiple research databases and conducting keyword cross-searches was employed in the present work. In terms of timing, it can be noted that China’s focus on energy conservation and emission reduction began to intensify with the 11th Five-Year Plan in 2006, marking the start of low-carbon development in highway transportation. Consequently, this study’s time frame from 2006 to 2024 encompasses the latest research findings and evolving policy dynamics.

Regarding database selection, comprehensive use of resources such as Crossref, government portal websites (including the official site of the National Development and Reform Commission) and international agency reports from organizations (like the IEA, the World Bank, etc.) allowed tracing cutting-edge international research in this domain. The official government website also provides a detailed understanding of various policy orientations, facilitating access to pertinent policy documents and insights into national development trends. The international agency reports offer a global perspective, providing industry analysis from multiple viewpoints.

For the keyword settings, the present work focused primarily on promoting the renewal and improvement of the low-carbon transportation system within the context of the Paris Agreement. This included exploring low-carbon technologies for power plants, alternative energy sources, and NEV-driven technologies, and evaluating policy formulation and current application scenarios. To aid in this process, across each database, using terms to expand the search scope and accurately locate the necessary documents, the following keywords were employed:

- (‘low-carbon transport’ or ‘decarbonization’) and (‘China’ or ‘policy’ or ‘technology’) and (‘road’ or ‘vehicle’ or ‘infrastructure’);
- (‘low-carbon transportation’ or ‘sustainable transportation’) and (‘Paris Agreement’);
- (‘electric vehicles’ or ‘fuel cell vehicles’) and (‘low-carbon technology investment’);
- (‘government intervention’ and ‘Transportation’) and (‘2009–2025’);
- (‘transportation decarbonization’ or ‘emission reduction’) and (‘strategic recommendations’);

- ('eco-friendly road infrastructure' and 'Sustainable transportation') and ('innovation');
- ('carbon neutrality' and 'transportation') and ('technology development maturity').

Given the vast amount of retrieved literature, the present work established inclusion and exclusion criteria to ensure the quality and relevance of the literature during screening and evaluation. Table 4 outlines the optimized screening criteria.

Table 4. Screening standard optimization.

Selection Criteria	Inclusion Criteria	Exclusion Criteria
Research Topic	Clearly focuses on low-carbon technologies or policies in road transportation	Involves research on non-road sectors such as aviation or shipping
Document Type	Peer-reviewed papers, government white papers, statistical yearbooks	Unverified industry reports, social media comments
Data Support	Provides verifiable empirical data or case studies	Pure theoretical analysis or policy recommendations lacking data support
Geographical Scope	National or regional collaborative studies (e.g., Beijing–Tianjin–Hebei, Yangtze River Delta)	Single city case studies (e.g., analysis of charging pile layout in Xiamen only)
Timeliness	Reflects technological progress or policy innovation post-2015	Does not include strategic adjustments after the 'Dual Carbon' target (2020)

4. Multi-Level Synergy Mechanisms and Tri-Stage Pathways: A DTMLP Framework for Low-Carbon Transition Through Vehicle–Grid–Storage Integration

4.1. Techno-Environmental Paradox Under Landscape Layer Pressure: BEV Governance Through Systemic Integration

Against a 12.7% compound annual growth rate in motor vehicle ownership and a transportation fuel consumption exceeding 50% of total usage, China has emerged as the world's second-largest oil consumer. However, China's energy structure remains characterized by coal abundance, oil scarcity, and gas deficiency. In 2023, the domestic crude oil production to imports ratio reached 20,472:50,838 (indicating a self-sufficiency rate of merely 28.7%), revealing a critical structural imbalance in energy supply–demand dynamics. With 70% of imports traversing the Malacca Strait and 45% originating from the Middle East, China's oil import dependency has surged beyond 80% [41], substantially exceeding the 50% international energy security threshold. Compounded by escalating geopolitical uncertainties in global supply chains, the synergistic advancement of energy security strategies and carbon neutrality commitments presents formidable challenges, heightening the imperative for accelerated carbon mitigation initiatives.

As the World Resources Institute [42] projected, China's transportation sector is anticipated to reach peak carbon emissions between 2025 and 2035, with carbon neutrality mandated by 2060. Aligned with the IPCC's 1.5 °C mitigation pathway, a 60% reduction in transportation carbon intensity is required. Multimodal studies have further indicated that external costs associated with toxic emissions from motor vehicle will experience exponential growth over the next quarter-century. Under these dual constraints, the imperative for energy conservation has surpassed conventional policy response thresholds. The LCA data presented in Table 5, utilizing an optimal initial EV range of 564.2 km, reveal that BEVs exhibited a 58.2% decrease in operational-phase carbon emissions compared to ICEVs, with energy conversion efficiency tripling that of ICEVs [43]. This technological-environmental performance leap substantiates BEVs' strategic position as a critical pathway for addressing emission reductions and energy security challenges through systemic optimization.

Table 5. Typical carbon emissions and characteristic parameters at each stage for medium-sized electric and fuel vehicles.

Type	Production Stage (kg CO _{2eq.} /Vehicle)		Use Phase	Abandonment Phase	
	Exclude Batteries Production	Power Battery Production	Characteristic Parameters	Secondary Usage	Reclaim
ICEVs	6500	/	The combined fuel consumption (gasoline) is 0.08015 L/km [44]	/	580 kg CO _{2eq.} /vehicle
BEVs	8900	110	Power consumption: 13.4 kWh/100 km NCM532: 450 kg, 168 Wh/kg Charge-discharge depth: 80% Total designed mileage: 200,000 km (about 7 years) 28% loss of capacity (Agreed to reduce raw capacity by 4% per year)	−196 kg CO _{2eq.} /kWh [45]	Without power battery: 510 kg CO _{2eq.} /vehicle; (Hydrometallurgical recovery) power battery: −69.7 kg CO _{2eq.} /kWh [46]

While BEVs demonstrate substantial emission reduction advantages during the operational phase, their production phase carbon footprint paradoxically reaches 8900 kg CO_{2eq.} per vehicle—37% higher than those of ICEVs. This discrepancy primarily stems from an energy-intensive battery manufacturing processes and constraints on critical minerals like lithium and cobalt supply. Consequently, the emerging landscape-level pressure transmission and techno-institutional coordination challenges necessitate systemic policy interventions.

Although BEV proliferation may reduce crude oil import dependency, this introduces strategic mineral supply chain vulnerabilities requiring vigilant governance. Empirical studies have confirmed that BEV net emission reduction benefits must be systematically analyzed through LCA frameworks, which is fundamentally contingent upon the temporal alignment between operational-phase electricity mix decarbonization and technological substitution. Achieving a dynamic equilibrium between emission reduction and resource security demands policy architectures that transcend singular technological substitution. This requires establishing a multi-dimensional governance framework integrating energy system transition (clean electricity penetration), supply chain resilience enhancement (mineral sovereignty), and circular economy mechanisms (battery cascade utilization).

4.2. Regime-Layer Restructuring in BEV Policy Transition: Coalitional Competition and Co-Evolution

The evolution of China's BEV policy system reflects a transition from government-led initiatives to market-driven dynamics. This development has progressed through several stages, as shown in Table 6, including technology research and development (R&D), policy initiation, scale expansion, structural adjustment, market-oriented transformation, and full-scale competition. Central to this evolution is the dynamic interplay between technology-driven and cost-constrained coalitions.

Initially, the technology-driven coalition included the central government, NEV manufacturers, and grid companies, all operating under the premise that BEVs are the optimal solution for enhancing national energy security and achieving carbon neutrality.

Table 6. Development stage of BEV policy system in China (2006–2024).

Time Stage	Major Policy Documents	Policy Tool	BEV Measures	Market Penetration
Technology development Period (2006–2008)	➤ National Medium- and Long-Term Program for Science and Technology Development (2006–2020) ➤ Rules on the Access to Production of New Energy Autos (2007)	➤ Special R&D fund ➤ Technical Standards ➤ Development ➤ Demonstration operation	➤ Establish the research direction of BEV core technology (battery, motor, electric control) ➤ First definition of BEV access criteria	0% → 0.01% (→ represents change)
Policy Launch Period (2009–2012)	➤ Notice on Carrying Out the Demonstration and Promotion Pilot Project of Energy-saving and New Energy Vehicles (2009) ➤ Energy Conservation and New Energy Automobile Industry Development Plan (2012–2020)	➤ Central financial subsidy ➤ Local supporting policies (no lottery, no restrictions)	➤ Launch the ‘thousand vehicles in ten cities’ project (BEV priority in public transport and rental areas) ➤ Clear the ‘pure electric drive’ strategic direction ➤ Beijing and Shanghai will open special licenses for private BEVs	0.01% → 0.5%
Scale Expansion Period (2013–2015)	➤ Notice on Continuing the Promotion and Application of New Energy Vehicles (2013)	➤ Subsidy expansion ➤ Tax relief	➤ BEV subsidy according to endurance classification ➤ Standardization of charging interface	0.5% → 1.3%
Structural Adjustment Period (2016–2018)	➤ Notice on Adjusting the Financial Subsidy Policy for the Promotion and Application of New Energy Vehicles (2016) ➤ Parallel Management Measures for the Corporate Average Fuel Consumption and New Energy Vehicle Credits of Passenger Car Enterprises (2017)	➤ Subsidy reduction (technical threshold increased) ➤ Double Credit policy	➤ Set BEV technical threshold ➤ The double integral policy forces the car enterprises to transform	1.3% → 4.5%
Market Transition Period (2019–2021)	➤ Notice on Further Improving the Financial Subsidy Policy for the Promotion and Application of New Energy Vehicles (2019) ➤ New Energy Vehicle Industry Development Plan (2021–2035)	➤ Precision subsidy ➤ New infrastructure (charging pile incorporated into national infrastructure)	➤ Local subsidies will be abolished, and central government subsidies will be reduced by 50% ➤ The target of ‘20% BEV penetration rate in 2025’ is proposed ➤ The localization of Tesla forces the upgrading of the industrial chain	4.5% → 13.4%
Full-Scale Competition Period (2022–2024)	➤ Notice on the 2022 Financial Subsidy Policy for the Promotion and Application of New Energy Vehicles ➤ Interim Measures for the Comprehensive Utilization of New Energy Vehicle Power Batteries (Draft for Comment) (2023)	➤ Subsidy withdrawal (only for electric changing models) ➤ Carbon footprint management (mandatory disclosure of Lifecycle Emissions)	➤ Central financial subsidies are fully terminated (31 December 2022) ➤ Auto companies assume the main responsibility for battery recycling (recovery rate of 95%) ➤ 800 V high-pressure platform, ultra-fast charging technology popularization	13.4% → 40% (possible)

During the technology diffusion initiation phase (2006–2015), policy instruments, including fiscal subsidies and mandatory infrastructure development, catalyzed a remarkable surge in BEV market penetration, from 0.01% to 1.3%. However, the paradigmatic policy transition initiated in 2016 revealed structural deficiencies inherent in heavy-handed interventionist approaches. While the subsidy phase-out and Dual Credit Policy orchestrated by the Automotive Technology Promotion Alliance drove a 60% enhancement in battery energy density, they concurrently induced market signal distortion and cost-shifting externalities. Systemic policy evaluations exposed technical specification fraud in 45.5% of vehicle companies during the 2016 special audit, resulting in direct economic losses equivalent to CNY 1.67 billion (USD 230.62 million at 1:7.25 exchange rate), evidencing market failure risks stemming from miscalibrated policy instrumentation.

Fiscal constraints, strategic resource security thresholds, and lifecycle cost considerations led to local governments and traditional energy enterprises (primarily constituting cost-sensitive coalitions) being unwilling to accept certain policy measures. This dynamic catalyzed the refinement of policy tools, ultimately resulting in the introduction of more detailed technical standards and an emphasis on enhancing industry quality.

By 2020, the policy paradigm had evolved into a hybrid governance model characterized by market-endogenous drivers with government-strategic guidance. Fiscal incentives transitioned from consumer-end subsidies to R&D empowerment, while regulatory tools

shifted from administrative mandates to benchmark-based guidance. Empirical evidence showed BEV market penetration surpassing the 5% tipping point (inflection point of the S-curve) during this phase. This transition constituted an institutional coupling process, where energy security imperatives and climate governance responsibilities achieved strategic alignment through multi-coalitions, revealing a remarkable enhancement in policy sub-system synergy, marking a theoretical advancement in energy–climate policy co-evolution within the Chinese institutional context.

4.3. Niche Innovation: BEV Technology Breakthrough and Evolution

The operational efficacy of BEVs is fundamentally reliant on high-energy-density battery storage systems. As illustrated in Figure 2, the production of BEVs can be classified according to their respective battery type [47]. Among the predominant variations of power batteries are lead-acid, nickel-metal hydride, nickel-chromium, and lithium-ion batteries (LIBs), which include subcategories such as lithium manganese oxide (LiMn_2O_4 , LMO), lithium iron phosphate (LiFePO_4 , LFP), and lithium nickel cobalt manganese oxide ($\text{LiNi}_x\text{Co}_y\text{Mn}_z\text{O}_2$, NCM). The latter two technical branches cater to different market segments: the NCM series is favored for high-end models, due to its superior energy density, while the LFP series, with its comparatively lower energy density, serves the cost-sensitive low- to mid-range markets.

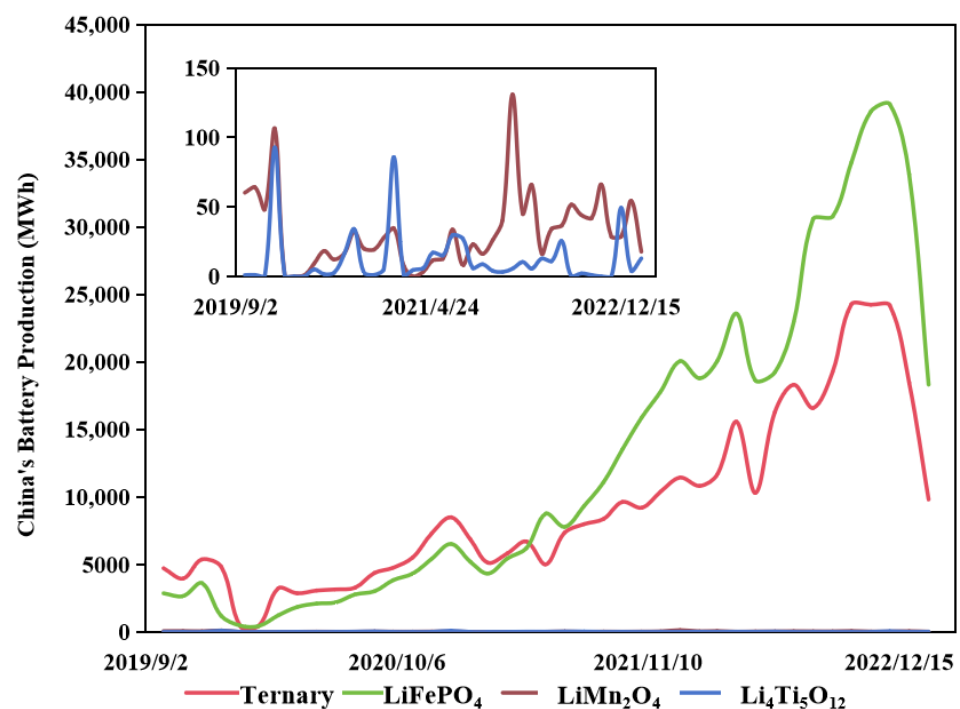


Figure 2. Production of various battery types utilized in pure electric vehicles [47].

Nevertheless, the selection of battery technology pathways necessitates a nuanced balancing of several competing considerations. The NCM series, despite its status as a prime choice for high energy density applications, raises concerns due to the substantial demand for cobalt and nickel, resulting in elevated production emissions [48]. Conversely, while the LFP series exhibits lower energy density, it is imperative to consider the ecological implications associated with the production of the graphite negative electrode, particularly the coal-based high-temperature graphitization process, which requires an energy-intensive input of more than 12,000 degrees per ton. Collectively, these factors contribute to a phenomenon that can be described as a ‘clean technology lock’.

Using LCA and input–output (I-O) methods, the life-cycle carbon emissions associated with different types of batteries have been evaluated, as detailed in Table 7. Between 2008 and 2020, the average energy density of lithium batteries increased sevenfold. However, LIBs face challenges such as diminished energy and power density at lower temperatures, as well as significant price volatility due to fluctuations in raw material supply.

Table 7. Characteristics and functional units of power batteries with corresponding total carbon emissions.

Battery Kinds	Characters	Energy Density (Wh/kg) [48]	Function Unit	Carbon Emission (kg CO _{2eq.})	Methods	Cycle Life
NCM111	High energy, high power, low cost, environmental protection, and long life [49], but the thermal stability is poor, with NCM and LFP series as the development mainstream.	160	1 kg	21.81	LCA [50]	1000–2000
			1 kWh	136.31	LCA [50]	
			1 kWh	130.4	CML CED [51]	
NCM532		170	1 kg	18.91	LCA [50]	
			1 kWh	111.24	LCA [50]	
			1 kg	20.97	LCA [50]	
NCM622		180	1 kWh	116.5	LCA [50]	
			1 kWh	93.56	CML-IA [52]	
			1 kWh	93.57	ReCiPe [52]	
NCM811		200	1 kg	21.74	LCA [50]	
NMC811			1 kWh	108.7	LCA [50]	
NMC622	LiFePO ₄	150–220	1 kg	8.2–9.1	MiLCA [53]	1000–2000
NMC523						
NMC111						
		140	1000 kWh	736.35	EPD2008 [54]	
			200,000 km	8827	CED CML-IA [55]	
			1 kWh	400	LCA [56]	
Li ₄ Ti ₅ O ₂	High safety, strong recyclability, low life span, and high maintenance cost [58]	50–80	1 kWh	1866	CED CML-IA [55]	3000–7000
LiMn ₂ O ₄		100–150	200,000 km	1866	CED CML-IA [55]	300–700
LiCoO ₂		150–200	1 km	149 (g)	ReCiPe [57]	500–1000
Lead-acid	Long service life, environmental protection but poor stability	20–35	1 kWh	102.76 (g)	ReCiPe [59]	250–1500
Ni-MH						
Ni-Cd						
NaPBA	Low-temperature performance and safety characteristics, high recovery value but low energy density [57]	105.5	1 kg	13.72	LCA [50]	>3000
		146.1	1 kWh	130.05		
			1 kg	14.76		
NaNMMT			1 kWh	101.03		
		133.5	1 kg	8.47		
NaMMO			1 kWh	63.45		
			1 kg	9.55		
NaMVP		129.6	1 kWh	73.69		
			1 kg	13.4		
NaNMC			1 kWh	115.62		
	NaS	116	1 kg	13.9		
			1 kWh	119.83		

4.3.1. Battery Lifecycle Carbon Footprint Contradictions and Low-Carbon Synergy Mechanisms

Considering the comprehensive life cycle of battery production, the current state of battery technology reveals a complex interplay of contradictions among efficiency, resource utilization, and environmental impact. The battery production phase involves the extraction and processing of various materials. As illustrated in Figure 3, the variances in emissions related to different battery material systems are primarily tied to elements such as cathodes, cathode active materials, forged aluminum, electrolytes, and casings. Notably, cathode materials significantly contribute to the carbon, water, and material footprints, with their relative impact increasing in line with the concentrations of nickel or cobalt in the battery. This is primarily due to the elevated carbon emissions associated with the mining and refining processes of these metals.

With advancements in lithium-rich low-carbon battery technologies, such as lithium-air batteries, the environmental impact during production could be reduced by 4 to 9 times compared to traditional LIBs [60]. Additionally, sodium-sulfur (NaS) batteries significantly reduce emissions when powered by electrical energy [50]. The development of lithium-rich, low-carbon technologies is becoming vital, focusing on enhancing cathode active materials and advancing complementary technologies like sodium-ion batteries (SIBs). Notably, as illustrated in Figure 4, when the carbon emission factor of electricity rose from

0.25 kgCO_{2eq}/kWh (in Europe) to 0.56 kgCO_{2eq}/kWh (in China), the lifecycle carbon emissions of LFP or LMO batteries increased by 14.4% or 2.8%, respectively.

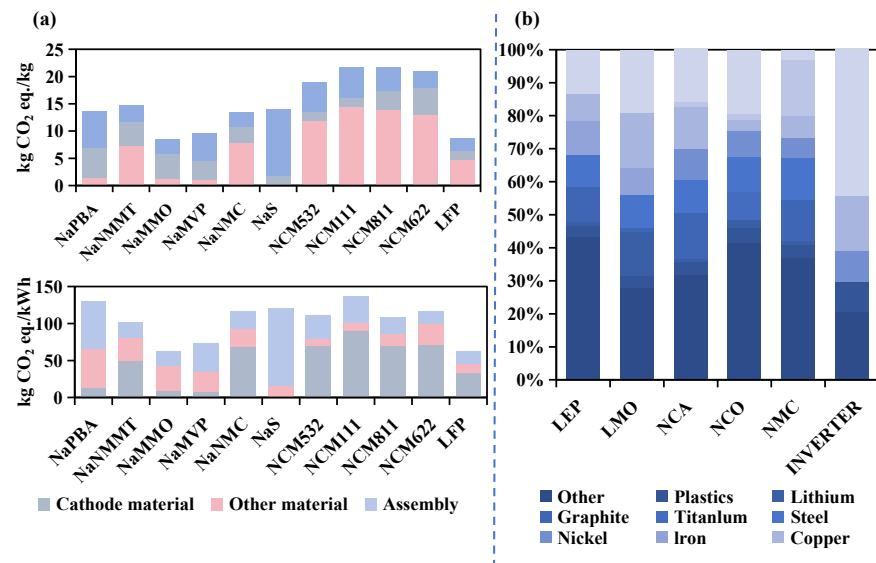


Figure 3. Carbon emissions of batteries: (a) associated with electrode materials [50]; and (b) ratio share of various materials [56].

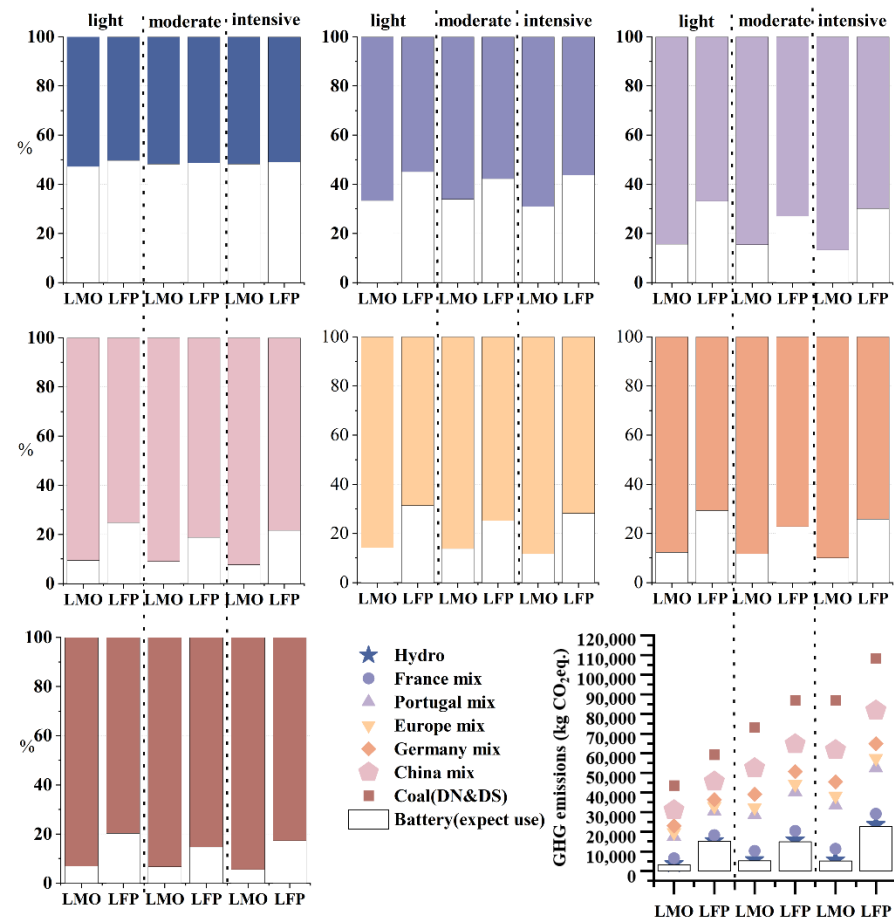


Figure 4. Carbon emissions of LMO and LFP batteries under different power generation combinations [55].

The geopolitical risk associated with the resource supply chain further complicates the carbon-locking process at the production level. The existing international monopoly

on cobalt and nickel resources results in high import costs, and SIBs may offer a viable alternative. China's sodium resource abundance stands at 2.6%, representing 23% of the global supply, making it completely autonomous and controllable. Additionally, as presented in Table 7, the carbon emissions of NaMMO battery systems amounts to only 63.45 kgCO_{2eq.}/kWh, with an energy density of 133.5 Wh/kg, which is 41% lower than that of comparable LIBs. Importantly, the low-temperature performance of SIBs (with a capacity retention rate above 85% at −20 °C) and their thermal stability address the safety concerns associated with lithium batteries, paving the way for increased adoption of BEVs in colder alpine regions. However, the transition to new technologies is not a linear process; while the cycle life of SIBs surpasses that of lead-acid batteries, their industrialization is hindered by challenges in optimizing electrolyte formulations and electrode structure. Consequently, the consumption of raw materials and energy efficiency are critical factors that significantly influence the environmental impact of the production process. Battery manufacturing contributes substantially to the ecological consequences of BEVs, accounting for over 30% of total carbon emissions [61]. If these challenges remain unaddressed, projections indicate that environmental impacts could increase by more than 40% [62].

The structural contradictions of clean technology path dependency underscore the necessity for synergistic integration of battery cascade utilization and recycling technologies. Taking LFP batteries as an exemplar, their extended life cycle characteristics (post-retirement capacity retention $\geq 70\%$) render them ideal for incremental applications in energy storage systems [63]. Through a 8–18 year lifespan extension, this approach could indirectly reduce new battery production demand, doubling the emission reduction advantages of BEVs [64]. For NCM/NMC batteries, pyro-metallurgical recycling (net emission 12.9 kgCO_{2eq.}/kWh) maintains an environmentally net positivity post-cascade utilization-efficient recovery of nickel-cobalt metals (recovery rate $> 95\%$) and offsets the ecological costs associated with virgin mineral extraction [65]. Conversely, direct physical recycling of LIBs post-secondary utilization [66] results in significantly lower carbon emissions, approximately 0.037 kg CO_{2eq.}/kWh. However, this approach must be complemented by high-consistency cell sorting (e.g., an AI sorting accuracy of over 98%), or else material degradation will increase costs. The connection between secondary utilization and recycling technology should be informed by dynamic decision-making regarding the residual value of batteries. For example, NMC111 batteries are prioritized for energy storage if their residual value exceeds 30% after secondary utilization. If their capacity falls below 50%, they should be redirected to either the plasma fire method (with a net emissions of −0.12 kg CO_{2eq.}/kWh) or the wet recycling method [67].

From a policy synergy perspective, establishing a battery life cycle traceability certification system (Battery Passport) constitutes a critical institutional innovation for dynamic state of health (SOH) monitoring. Empirical evidence has demonstrated that when LFP battery SOH thresholds fall below 60%, subjecting them to compulsory hydrometallurgical recycling (carbon footprint −24.58 kg CO_{2eq.}/kWh) maximizes negative carbon benefits [46]. Prospective techno-economic analyses revealed that a modular architecture design can enhance disassembly efficiency by, reducing the life cycle integrated costs of cascade utilization and recycling by 70% [68]. This breakthrough provides technical feasibility for constructing an industrial symbiosis model of cascade utilization and low-carbon regeneration, positioning this as an industrialized closed-loop paradigm for energy storage systems within the new power grid.

4.3.2. Power Transition Pressures and Policy Synergy: Battery Life Cycle Carbon Mitigation Mechanisms

China's coal-based power system has significantly elevated the carbon intensity of energy portfolios, generating systemic pressure on the life cycle carbon emissions of power

batteries. This pressure mechanism operates through two pathways: (1) deep reliance on high-carbon electricity in battery manufacturing (coal power share > 60%); and (2) lagging clean electricity penetration relative to charging infrastructure expansion. As illustrated in Figure 5, during 2016–2022, China’s public charging stations grew 62% annually while coal power share decreased by 9%, resulting in a 38% rise in indirect carbon emissions from charging. Notably, charging infrastructure exhibits marked regional heterogeneity, with first-tier cities demonstrating a 4.7-fold higher charging density than third-tier cities, and with exponential growth projected over the next decade. Econometric analysis revealed each 10% increase in electric vehicle loading gives an 18% marginal growth in grid load demand [69], foreshadowing intensified baseload regulation pressures from EV scaling.

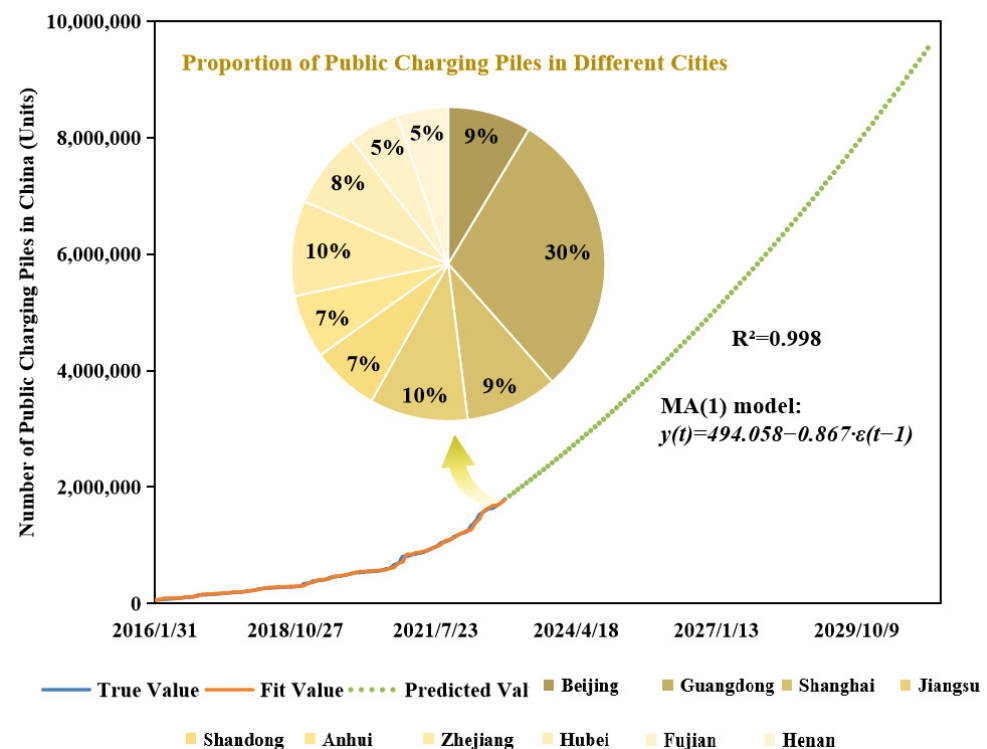


Figure 5. Predicted fitting curve for the monthly number of public charging stations in China from 2016 to 2030 utilizing time series methodologies.

The low-carbon transition of the power sector constitutes the pivotal leverage for resolving this dilemma. In China’s power structure, each 10-percentage-point decrease in coal power share (replaced by wind/hydro) reduces the battery life cycle carbon footprint by 7.9–8.2% [70]. Empirical modeling shows charging stations with 20% PV integration achieve daily emission reductions of 5411.18 kg CO_{2eq.}, decreasing the vehicle–grid synergistic carbon flow by 10.818 tons CO_{2eq.} [71]. This technology–institution synergy demonstrates regional heterogeneity—renewable-rich areas exhibit a 2.3-fold higher emission reduction elasticity than traditional load centers. The scenario projections in Figure 6 indicate that under China’s policy targets of 22% and 100% coal power substitution by 2030 and 2060 [72], GHG emissions from battery production will decline by approximately 30% and 90% compared to 2020 baselines [73]. When renewable penetration surpasses the 60% threshold, nonlinear decay characteristics will emerge in production-phase (electrode material smelting) and EoL-phase (recycling) emissions, which would signify the evolution of power decarbonization and transport electrification from linear superposition to systemic coupling.

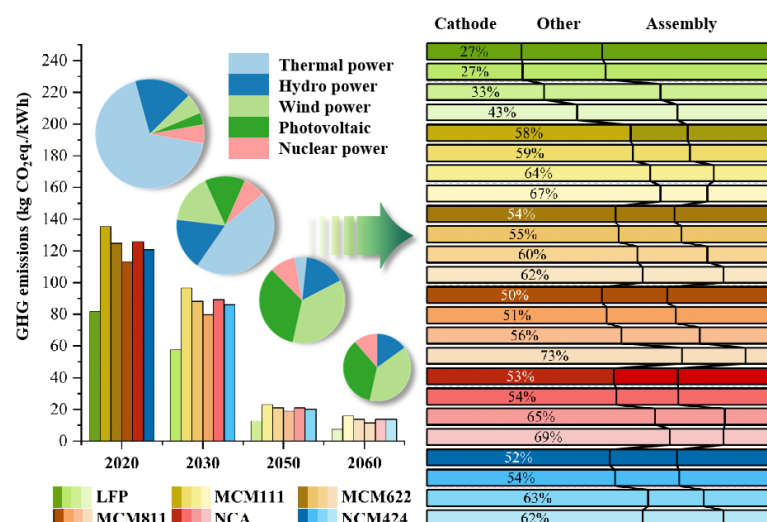


Figure 6. Predictions of carbon emissions associated with different strategies for China's power generation in the future [73].

Meanwhile, establishing microgrid systems, with effectively integrated variable renewable energy sources like wind and solar through source–grid–load–storage coordination, can exert pressure transmission mechanisms on BEV charging carbon management, considering life cycle economic–environmental performance. Yinchuan, a provincial capital city in northwest China, demonstrated that complementary multi-energy systems (integrating adjacent PV resources and storage facilities) elevated green power share to around 60% in industrial parks, reducing unit green electricity costs by 27%. This transition requires dual technological–institutional innovation: nationally, revising electricity market rules to enable distributed energy aggregator participation in spot trading; locally, advancing distribution network restructuring and load aggregator mechanisms [74]. Furthermore, intelligent management methods can automatically adjust the charging time according to the electricity price, to alleviate the burden on the grid during peak hours and improve overall economy [75].

From a national policy perspective, while power structure decarbonization serves as strategic leverage for mitigating battery environmental impacts, a comprehensive assessment of renewable energy's full-chain ecological costs remains imperative. Although wind and PV exhibit near-zero operational emissions, their manufacturing processes have critical material scarcity risks [76]: studies have projected about 20-fold increases in neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and terbium (Tb) demand for offshore wind turbines by 2040 [77]. LCA data reveal a life cycle GHG intensity of 5.84–16.71 gCO₂eq./kWh for onshore and 13.30–29.45 gCO₂eq./kWh for offshore turbines, showing marginal increases with unit capacity, rotor diameter, and hub height, yet offshore scale-up demonstrates a lower emission reduction elasticity [78].

Regarding the above, policy toolkit optimization must transcend singular technological breakthroughs; empirical evidence shows that synergistic implementation of coal power carbon differential pricing (\$0.0069/kWh) and green power subsidies (\$0.0041/kWh) with renewable portfolio standards can enhance BEV emission reduction efficacy over battery energy density improvements alone [79]. The Yangtze River Delta's 'Zero-Carbon Charging Corridor' pilot achieved an emission reduction elasticity coefficient of 1.87, yet microgrid expansion remains constrained by institutional barriers, including cross-regional green certificate incompatibility and the undefined market entity status of distributed storage [80].

In addition, the disposal costs associated with end-of-life wind turbine components are substantial. Current waste management strategies for wind turbine blade disposal predom-

inantly include landfill and incineration. Despite heavy metals' substantial economic value and recycling potential, documented recovery rates are alarmingly low, with less than 1% of materials recycled. Existing recycling technologies—such as mechanical, thermal, and chemical methods—are plagued by inherent limitations, including degradation of material quality, high energy consumption, and protracted processing times [81]. The projected GWP of the wind turbine blade waste treatment process is estimated to remain exceedingly high, ranging from 150.2 to 188.3 Mt CO_{2eq.} in 2050 [82]. Thus, extending service life and fostering technological innovations are critical to effectively reducing material demand and realizing the zero-carbon potential of renewable energy sources.

4.3.3. Techno-Parametric Sensitivity and Optimization Pathways in Operational Battery Carbon Mitigation

Carbon mitigation logic during the battery operation phase underscores the complexities of technological optimization. As evidenced in Table 7, significant round-trip efficiency disparities emerge across form factors (such as pouch, cylindrical, and prismatic) and cathode material systems, with efficiency metrics reflecting energy loss rates during complete charge–discharge cycles. These technical parameters mediate the carbon emission intensity of operational vehicle units through energy conversion efficiency effects.

Battery characteristics encompass a range of factors, including chemical composition, internal efficiency, weight, and power, along with design parameters such as electrode configuration, porosity, and charge–discharge cycle performance. For instance, LIBs exhibit the lowest carbon emissions during their operational phase due to their 90% round-trip efficiency. In contrast, with an efficiency of 75%, vanadium redox flow batteries result in 37% higher emissions. Furthermore, the low energy density of these batteries necessitates deploying a more significant number of comparable operational examples, leading to an increased system mass that negatively impacts carbon emissions, underscoring the urgent need to enhance energy density [56].

Moreover, material-constrained trade-offs exist between energy density and cycle life. As illustrated in Figure 7, frequent charge and discharge cycles accelerate capacity degradation, resulting in an increase in carbon emissions per functional unit [56]; however, NCO-LTO batteries significantly outperform other types in terms of cycle longevity, achieving a 50% reduction in life cycle emissions during high-frequency cycling (4 cycles/day). This highlights the crucial impact of user charging behavior and management strategies on optimizing battery performance.

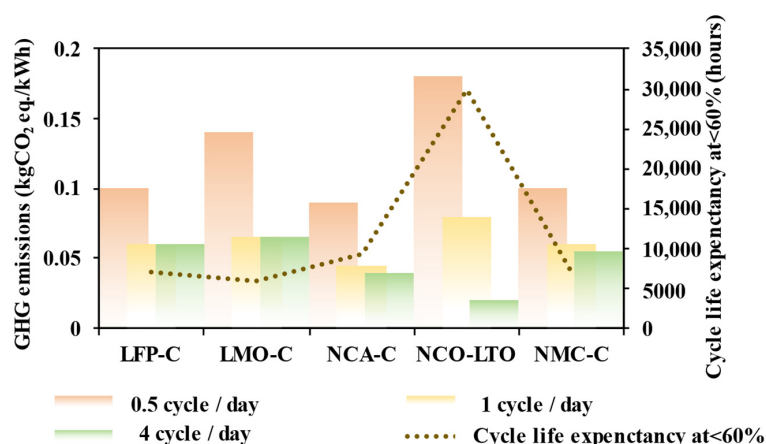


Figure 7. Comparison of carbon emissions of various batteries under different cycles [56].

As illustrated in Figure 8, when the relationship between carbon emissions and key operational parameters (such as round-trip efficiency, cycle frequency, and power consumption)

was further quantified using empirical data [83], a weak dependence of emissions on average power output was seen (a 3% reduction for a 5% increase in power), but with a high sensitivity to round-trip efficiency and a 3% reduction in emissions for every 1% gain in efficiency.

Elevated temperatures compound these challenges; as illustrated in Figure 9, under operating conditions of 45 °C, the cycle count sharply declined from 2810 to 930. Implementing optimized thermal management, such as maintaining a temperature of 25 °C, in conjunction with controlling the average state-of-charge (SoC) at 50% and depth-of-discharge (DoD) at 30% could help delay efficiency decay and reduce emissions by 12% [84]. Therefore, developing high-energy-density batteries with a prolonged cycle life necessitates co-optimizing material systems, thermal management, and user-centric charging protocols.

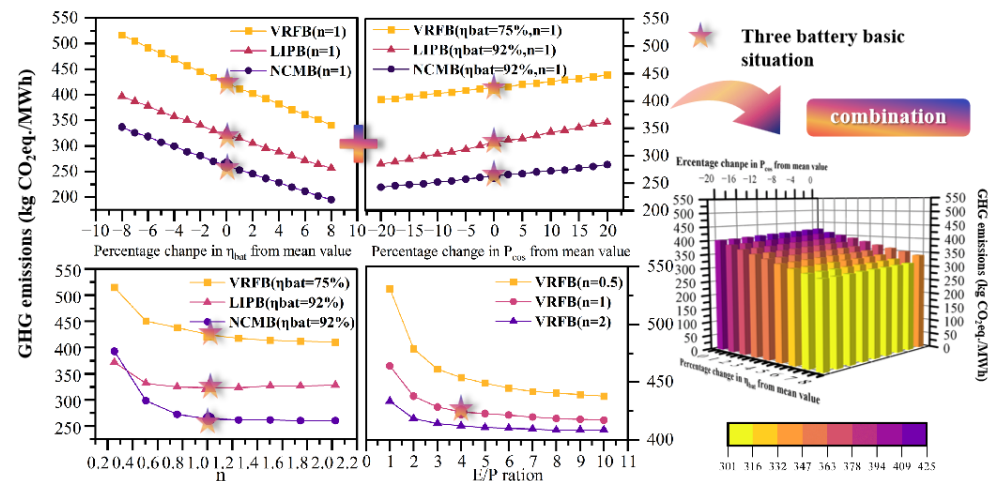


Figure 8. Correlation of carbon emissions to battery performance, including round-trip efficiency, cycle frequency, power consumption, energy, and power ratio [83].

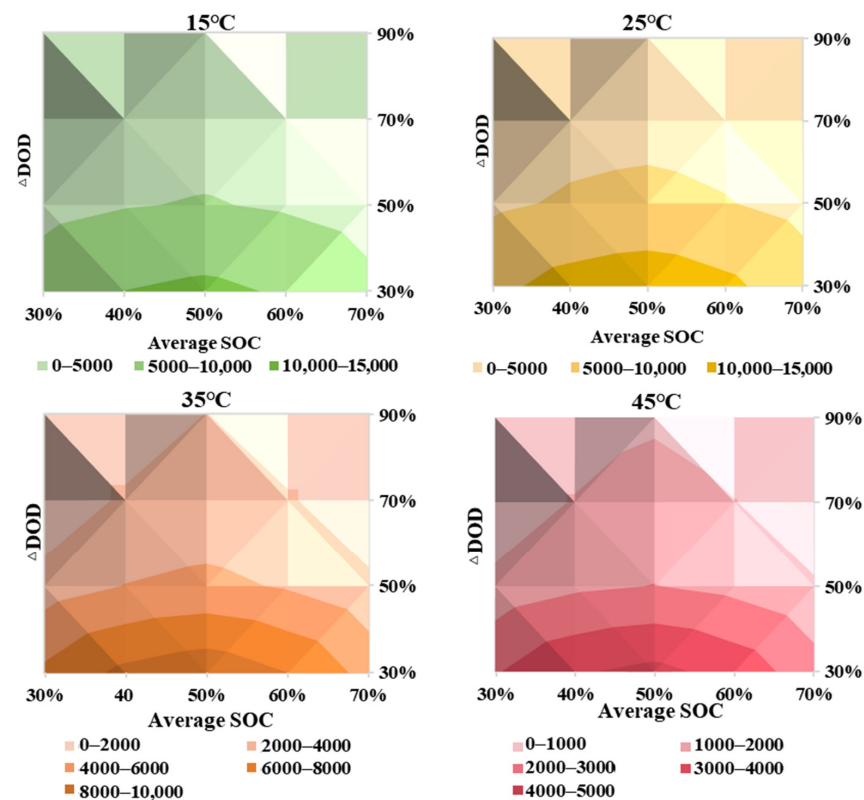


Figure 9. Comparison of the degradation rates of lithium-ion battery cathodes under different cycling frequencies [84].

4.4. Multi-Level Synergy and Tri-Stage Pathways for BEV Development: A DTMLP Framework for Low-Carbon Transition

The DTMLP framework for BEV development reveals a dynamic interaction mechanism at the landscape, regime, and niche levels. The macro goals of energy security and carbon neutrality exert policy pressure from the landscape to the regime level, triggering dual responses: adaptive adjustments to external pressures, coupled with institutional innovation driven by internal policy coalitions. This dynamic equilibrium has led to accelerated iteration and fragmentation of policy tools in recent years. Notably, regime-level responses exhibit bidirectional modulation of niche-level technological innovation: breakthroughs in battery technology strengthen policy confidence (positive incentive), while delays in recycling systems necessitate standardized policy adjustments (negative feedback). The technological trajectory shifts from single-performance competition to a three-dimensional synergy of resources, environment, and costs. However, institutional design is critical for selecting technology and preventing an inefficient lock-in.

A tripartite synergy involving material substitution, process innovation, and system restructuring is required for achieving carbon neutrality in power batteries, as seen in the evaluations in Sections 4.3.1–4.3.3:

- (i) Material substitution: Developing SIBs using China's sodium resources with production carbon emissions of 63.45 kg CO_{2eq}/kWh (45% lower than that of NCM622) [50]. Utilizing sulfide electrolytes (with ionic conductivity of 25 mS/cm) [85] can elevate energy density to 400 Wh/kg [86], while using less lithium and alleviating the reliance on foreign resources. However, the challenges of balancing energy density and cycle life remain [87].
- (ii) Process innovation: Integrating green power direct supply and dry-electrode technology [86] aligns with the EU's carbon footprint requirements. Blockchain battery passports enable automated recycling (Ni/Co wet recovery >98.5%).
- (iii) System restructuring: Adopting V2G dynamic pricing to facilitate PV-storage synergy (like Zhejiang pilot: 1.63 million kWh/3 days). Implementing blockchain battery passports to catalyze automatic recycling, achieving a wet recovery rate of over 98.5% for nickel and cobalt, and reducing carbon intensity by −24.58 kg CO_{2eq}/kWh [46].

The system operates through a three-stage pathway: Material breakthroughs resolve resource constraints (Na substitution/solid-state Li reduction) → Policy guidance drives process innovation (carbon footprint standards/recycling certification) → Market mechanisms enhance system efficiency (V2G/storage synergy), culminating in a 'Vehicle–Grid–Storage' integrated carbon-negative ecosystem.

5. Multi-Level Synergies and Fractures in Policy–Technology–System Integration: An MLP Framework for Hydrogen Fuel Cell Electrical Vehicles Pathways

5.1. Hydrogen Fuel Cell Electric Vehicles: Potential and Challenges Under the Landscape Layer

Hydrogen is a fuel with high energy density but zero carbon emissions, and it can be employed to generate power via the combustion approach (in ICE) and/or electrochemical route (in fuel cells). Hydrogen fuel cell electric vehicles (HFCEVs), compared to ICEVs, can reduce energy consumption by approximately 29% to 66%, and GHG emissions by a significant 31% to 80% [88]. Notably, the benefits associated with hydrogen refueling vehicles become increasingly pronounced with more significant specifications in the short term, showing a carbon reduction effect that is 3.72% higher than that of vehicles using electric alternatives. Meanwhile, HFCEVs generate electrical power onboard through an electrochemical reaction between hydrogen and air, instead of relying on electricity

sourced from the grid, as illustrated in Figure 10, which is advantageous for advancing deep decarbonization efforts within the road transportation sector.

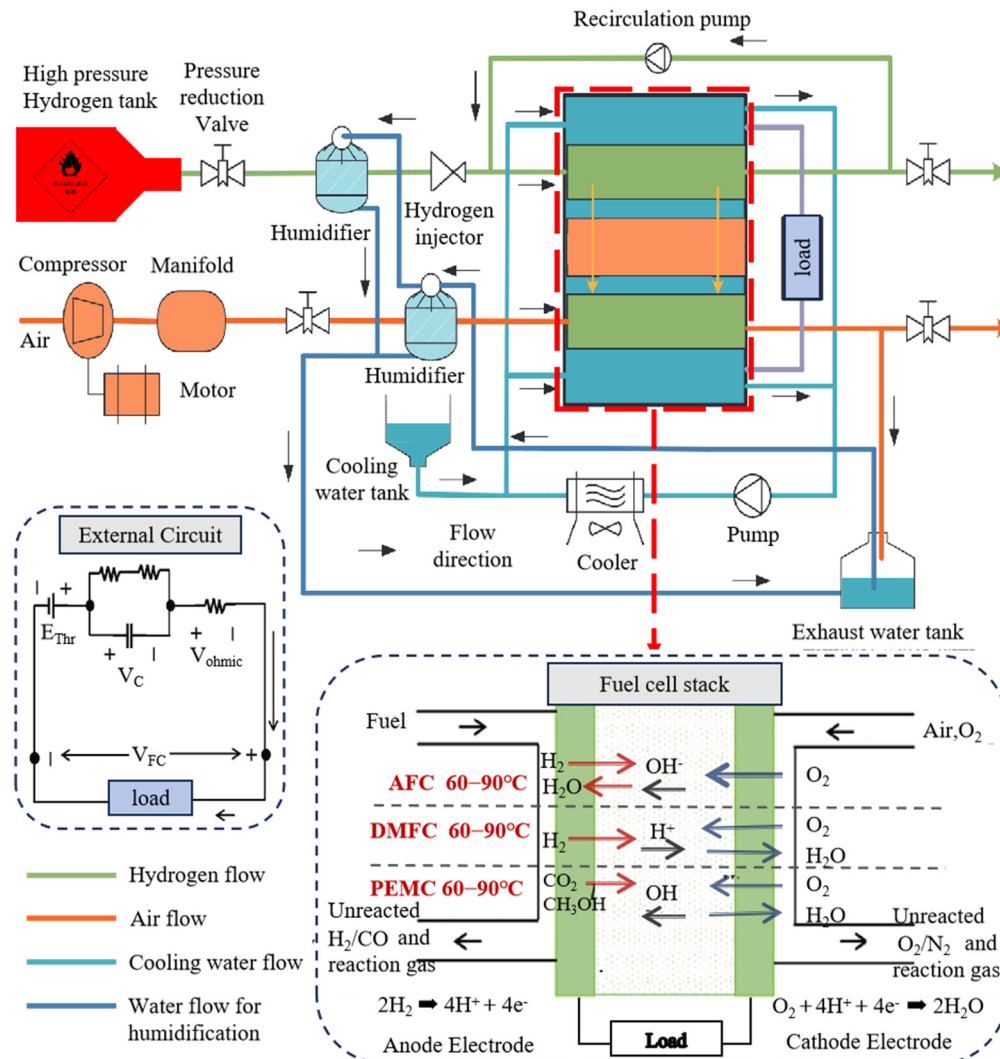


Figure 10. Principle of operation of hydrogen fuel cells.

Optimistic forecasts suggest that global investments in hydrogen energy within the transportation sector may reach approximately USD 8.83 billion by 2030 [89]. In China, hydrogen fuel is projected to satisfy 28% of the energy demand for transportation by 2050 [90], potentially resulting in a notable reduction in carbon emissions, estimated at 1.7 billion tons annually by 2060 [91]. To meet the goals articulated in the ‘Dual Carbon’ initiative, projections estimate that, by 2035, the number of FCEVs in China will reach 549,500 units (in a low-growth scenario), 2,351,700 units (in a baseline scenario), and 8,844,100 units (in a high-growth scenario) [92]. Furthermore, hydrogen fuel cells can help heavy trucks achieve long driving ranges (exceeding 1000 km) with short refueling times, which positions hydrogen as a viable alternative in long-distance freight transportation scenarios, which purely electric technologies do not address effectively.

However, China’s FCEVs sector faces multifaceted challenges. First, a stark disconnect exists between market penetration and policy targets: in 2023, FCEV sales reached only 6000 units, three orders of magnitude lower than battery electric vehicles (BEVs) at 6 million units. Second, the carbon-intensive hydrogen production structure [26], with 99% reliant on fossil fuels (62% from coal), elevates life cycle emissions, undermining

FCEVs' decarbonization potential. Concurrently, hydrogen infrastructure lags critically, with a refueling station density of <0.05 stations/10,000 km², compared to 5.8 EV charging stations/km². Path dependency on diesel-powered heavy trucks in heavy industries further entrenches the misalignment between hydrogen technology and the low-carbon energy transition.

Meanwhile, global competition intensifies these pressures: the EU's Hydrogen Strategy targets 10 million tons production and 10 million tons importation of renewable hydrogen by 2030, leveraging the Carbon Border Adjustment Mechanism (CBAM) to decarbonize supply chains, while Japan is building transnational liquid hydrogen supply chains (e.g., imports from Australia) under its Hydrogen Society vision. In contrast, China's Medium- and Long-Term Hydrogen Industry Plan (2021–2035) outlines a three-phase roadmap but struggles to bridge the gap between its current $<1\%$ green hydrogen share and the future target. This 'technological–energy system fracture effect' traps FCEVs in a semi-commercialized phase, where emission reduction commitments face a "green premium" due to upstream high-carbon lock-ins.

5.2. Restructuring the Policy Regime Layer: Alliance Competition and Institutional Fractures in China's HFCEV Governance

China's HFCEV policy framework has evolved through dynamic interactions among three competing alliances: the industry collaboration alliance, the cost-constrained alliance, and the regulatory regime alliance. Since the '863 Program' (National High-Tech Research and Development Program) initiated research and development in fuel cell technology, policy instruments have transitioned from a singular R&D subsidy to an integrated system encompassing technical standards, market incentives, and carbon constraints, as detailed in Table 8. However, inter-alliance conflicts have caused policy implementation fractures:

- (i) The regulatory alliance (central ministries) prioritizes green hydrogen for strategic security, consolidating standards across six agencies (including the Standardization Administration of China, the National Development and Reform Commission, the Ministry of Industry and Information Technology, the Ministry of Ecology and Environment, the Ministry of Emergency Management, and the National Energy Administration) through the Guidelines for the Construction of a Standard System for the Hydrogen Energy Industry (2023 Edition), to unify carbon accounting and safety protocols. Yet fragmented horizontal coordination weakens fiscal mechanisms—over USD 1.38 billion in hydrogen city-cluster subsidies have mostly been allocated to refueling stations [93], neglecting hydrogen cleanliness and perpetuating fossil-based production dominance.
- (ii) The cost-constrained alliance (local stakeholders) resists aggressive transitions by emphasizing green hydrogen's cost premium over gray hydrogen [26,92], leveraging tax incentives (e.g., 50% resource tax cuts for coal-based hydrogen) to concentrate 85% of 2023 hydrogen truck sales in gray-hydrogen-rich regions.
- (iii) The industry collaboration alliance (automakers–research institutes) promotes incremental innovations like toll exemptions for hydrogen trucks and dedicated land quotas for stations, while market-driven initiatives (e.g., JD.com/SF Express and other logistics enterprises purchasing 5000 hydrogen logistics vehicles) stimulate demand. Resource asymmetry persists: the regulatory alliance controls technical standards (e.g., Fuel Cell Stack Lifespan Testing Methods), while local actors attract downstream players through fiscal privileges.

Policy instrument iterations reflect shifting power dynamics: pre-2021, the technology-driven alliance enforced 'performance-based subsidies', requiring green hydrogen use and a ≥ 500 kg/day refueling capacity. However, only 12 of 41 projects met the criteria,

triggering a backlash. The Fuel Cell Vehicle Demonstration and Application Management Measures (2023 Revision) introduced ‘carbon footprint thresholds’, while allowing local special bonds for stations—a double-edged sword that increased fiscal burdens.

Table 8. Summary table of China’s fuel cell electric vehicle policy since 2001.

Time Stage	Policy	Core Measures	Technical Impact	Implementation Effect
2001–2010	National High-tech R&D Program of China (863 Program) (2001)	For the first time, fuel cell vehicles were included in national science and technology projects to fund the research and development of key technologies.	Started R&D and completed fuel cell vehicle prototypes.	Laid the technical foundation, but the commercialization capacity was insufficient.
	Interim Measures for the Management of Financial Subsidies for the Demonstration and Promotion of Energy-saving and New Energy Vehicles (2009)	RMB 200,000 for fuel cell passenger vehicles, RMB 300,000 for light passenger vehicles, and RMB 500,000 for medium and heavy passenger vehicles, encouraging enterprises to participate in demonstration operations.	Promoted enterprises to develop fuel cell commercial vehicles.	In 2010, less than 100 vehicles were promoted, mainly for demonstration projects such as the Beijing Olympic Games and the World Expo.
2011–2020	Technology Roadmap for Energy Saving and New Energy Vehicles (2016)	Target: 5000 units in 2020, 50,000 units in 2025, and 1 million units in 2030; the subsidy scope was extended to logistics vehicles and heavy trucks.	Accelerate the localization of fuel cell system and improve the power density of the stack.	In 2020, the cumulative sales volume was about 7000 units, and commercial vehicles accounted for more than 90%.
	Recommended Model Catalogue for the Promotion and Application of New Energy Vehicles	HFCEVs will be included in the catalog and enjoy a purchase tax reduction, priority right of way, and other policies.	Promote enterprises to achieve mass production of FV systems.	The cost of fuel cell systems will fall to 80% by 2020
2020 Year to now	Notice on Launching Fuel Cell Vehicle Demonstration Projects (2020)	Promote 20,000 HFCEVs in Beijing–Tianjin–Hebei and the Yangtze River Delta, and reward according to the demonstration effect; the localization rate of key parts was 50%.	Accelerated the localization of the graphite bipolar plate and proton exchange membrane, but the catalyst still depended on imports.	In 2023, promoted more than 15,000 vehicles, built 474 hydrogenation stations, and reduced the green hydrogen cost to USD 2.90/kg
	Hydrogen Energy Industry Development Plan (2021–2035)	Hydrogen energy is defined as an important part of the future energy system, and it is proposed that FCEV ownership will be 50,000 in 2025 and a hydrogen energy industry ecology will be formed by 2035.	Hydrogen energy is heavily concentrated in ports and mining areas, with a more than 15,000 h lifespan.	In 2023, the sales volume of hydrogen energy heavy trucks accounted for more than 60%, but the coverage rate of hydrogenation stations was insufficient (only covering major urban agglomerations).

Central–local disconnects have created a ‘rule-setting vs. resource competition vs. corporate path selection’ cycle. By 2023, China had built 474 hydrogen stations, yet with a severe regional imbalance (44% in Beijing–Tianjin–Hebei, Shanghai, Guangdong, Zhengzhou, Hebei, and other five city demonstration communities, <10% in central-west) and 70% operating below 40% capacity, revealing infrastructure–market misalignment. Breaking this rigidity requires expanding alliances to energy groups, leveraging carbon markets for resource allocation, and engaging in ISO/TC197 standardization to shift from ‘multi-layered embeddedness’ to systemic policy coordination.

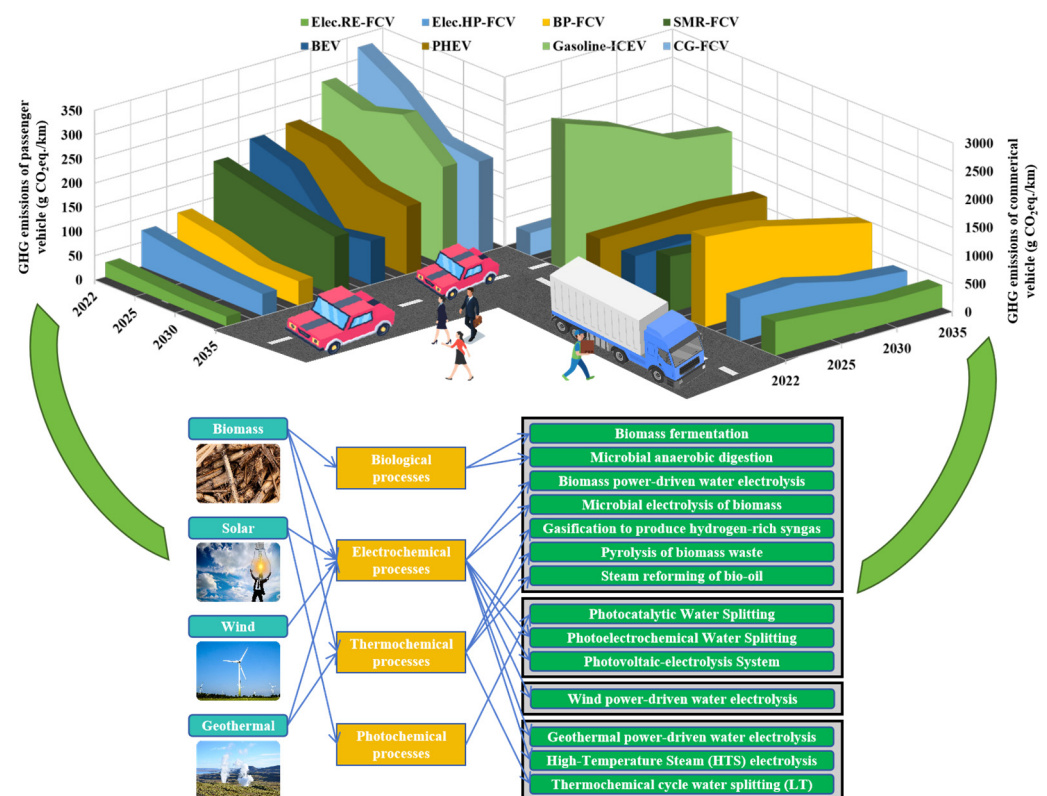
5.3. Multidimensional Challenges in Hydrogen Technology Synergy and System Integration

The technological advancement of HFCEVs confronts a fundamental paradox within the green-energy–security paradigm: the systemic coordination of hydrogen infrastructure development. As outlined in Table 9, hydrogen production demonstrates technological diversity through multiple carbon-containing feedstocks, with each pathway presenting unique technical merits. Crucially, the carbon intensity of HFCEVs is predominantly dictated by the selected hydrogen-generation methodology rather than the vehicular operation itself.

Figure 11 demonstrates the life cycle carbon emission trajectories for both passenger and commercial HFCEVs through to 2035, derived from GRA- BiLSTM model projections [92] and established green hydrogen pathways [99–101]. The emissions hierarchy reveals coal gasification (CG) as the most carbon-intensive hydrogen source in China’s context, preceded sequentially by steam methane reforming (SMR), biomass pyrolysis (BP), hydro-powered electrolysis (Elec.HP), and renewable-energy-based electrolysis (Elec.RE). Projections indicate a potential 5–10% reduction in per-unit emissions by 2035 through synergistic advancements in fuel efficiency, battery technology, and hydrogen production optimization. Notably, commercial vehicles persistently exhibit 18–25% higher life cycle emissions than passenger counterparts across all fuel types.

Table 9. Hydrogen production technologies: methods, feedstock sources, and advantages.

Methodology	Energy Source	Research Focus	Advantages
Coprecipitation, Hydrothermal, Sol-gel	Methanol	Hydrogen production via steam reforming of methanol (SRM)	High methanol conversion (91.5%), high H ₂ yield (90.9%), low CO selectivity (0.61% at 280 °C), optimal Cu/Zn ratio [94].
Dark Fermentation (DF), Co-precipitation, Hydrothermal, Sol-gel	Organic renewable carbon sources	Biomass-based hydrogen production using dark fermentation	High biohydrogen yield, improved bioconversion, and enhanced energy recovery through advanced pretreatments and designs [95]
Electrolysis using aqueous polyoxometalate (POM)	Native biomasses	High-efficiency hydrogen evolution from native biomass electrolysis	There is no noble-metal catalyst, low energy use, and the reaction can use sunlight/heat; no chemical pretreatment is needed [96].
Photo Fermentation, Pre-treatment (banana peels)	Brewery wastewater	Improvement in photo fermentative hydrogen production using pre-treated brewery wastewater with banana peels waste	Increased hydrogen yield via banana peel pre-treatment, optimized C/N ratio, and reduced ammonium [97].
Solar-driven steam-autothermal reforming	Solar energy, Natural gas	Solar energy driven steam and autothermal combined reforming system for hydrogen	Produces hydrogen, urea, electricity, and heat, powering 400 households with zero carbon emissions [98]

**Figure 11.** Prediction of carbon emissions of FCEVs by different hydrogen production sources [99–101].

The economic viability of renewable-derived “green hydrogen” presents a critical pathway, with IEA forecasts suggesting a 70–80% cost reduction by 2050 [102]. This economic transition is being accelerated by three concurrent technological developments: (1) Progressive cost declines in solar/wind generation; (2) Enhanced electrolyzer efficiency; and (3) Scaling effects in renewable infrastructure. Green hydrogen production via water electrolysis—powered by wind, solar, and geothermal sources—offers near-zero operational emissions but faces commercialization barriers from capital-intensive infrastructure requirements. Strategic integration of hydrogen refueling networks with smart grid architectures is a prerequisite for achieving emission equilibrium across production and utilization phases.

The current electrolyzer technology landscape reveals distinct cost–performance matrices, as illustrated in Figure 12 (U.S. Department of Energy classifies the development stages of major electrolysis technologies using Technology Readiness Level assessments [103]): Alkaline electrolysis (ALK), the most mature global technology [104], can achieve hydrogen

production costs of USD 5.00–5.50/kg H₂; proton exchange membrane (PEM) electrolysis can achieve USD 6.00–7.20/kg H₂ when powered by grid electricity; and proton-conducting solid oxide electrolytic cells (O-SOEC) cost USD 7.00–8.00/kg H₂ with natural-gas-assisted heating. Meanwhile, technological divergence creates complementary application scenarios: ALK dominates centralized production through scale effects (single-cell capacity up to 1000 Nm³/h), whereas PEM's dynamic response advantage (70% faster ramp rates than ALK [105]) suits distributed renewable energy systems, despite its high system cost premium from its catalyst requirements [106].

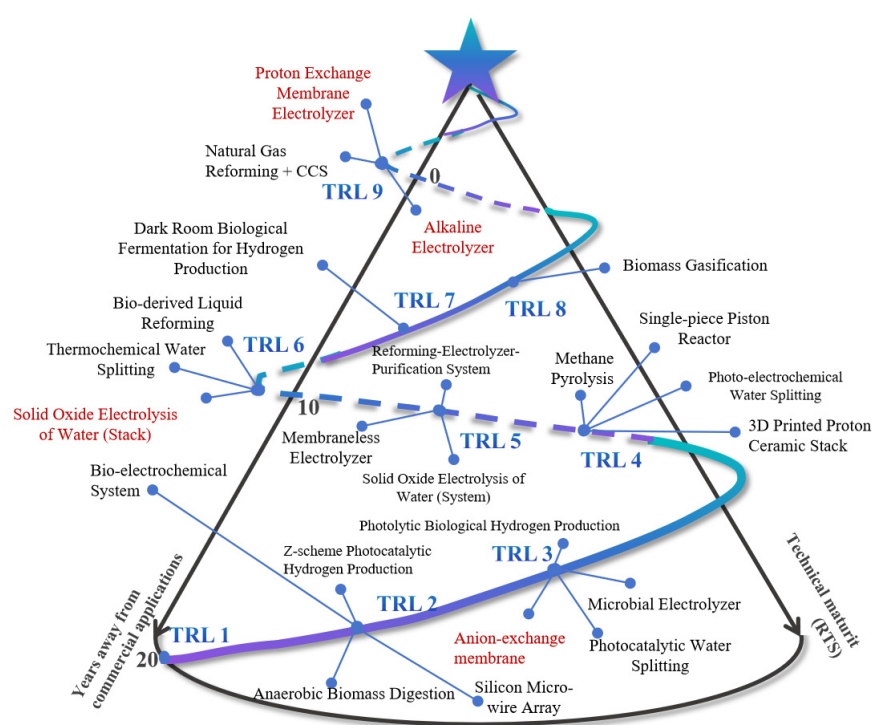


Figure 12. Development situation of point solution technology under TRL (technology maturity) division [103].

The industry is undergoing a paradigm shift from standalone hydrogen systems to multi-energy complementary networks [107], yet hydrogen storage/transport bottlenecks impede system optimization: Current limitations include a <40 kg/m³ storage density at 700 bar, 30–35% energy penalty for liquefaction, and spontaneous combustion risks during pressurized leakage [108]. Projected life cycle storage/transport costs for 2030–2050 fluctuate between USD 30.23 and 52.9/kg, with transportation distance being a critical determinant [109], necessitating location-specific solutions. Notably, PEM's high current density (>2 A/cm²) and millisecond-level response [105] provide unique advantages in renewable energy fluctuation management, though challenges persist in noble metal dependency [106].

Furthermore, hydrogen refueling infrastructure development requires overcoming three key constraints: (1) Safety protocols, encompassing leak detection and emergency response [110]; (2) Site selection, balancing supply chain logistics (raw material transport radius < 200 km), regional traffic patterns, and public acceptance; and (3) Storage/transport optimization through hybrid solutions (gas/liquid storage, on/off-site production). Innovative models like DC-interconnected stations [111] and modular multi-supply systems [112] can enhance market penetration efficiency by 76.7% and boost EV sales by 40% [113]. Technological breakthroughs must create synergies: electrolyzer efficiency improvements,

storage density optimization, and refueling network expansion form a trinity for scalable hydrogen deployment.

Regarding the above-mentioned factors, the systemic advancement of HFCEVs necessitates strategic alignment across multiple governance levels, yet it faces dual challenges of institutional inertia and technological-economic constraints. While long-term decarbonization objectives require landscape-level planning for green hydrogen ecosystems, subnational governments exhibit path dependency on gray hydrogen production methods, due to fiscal limitations and existing industrial infrastructure. This institutional-technological mismatch creates a circular dynamic where niche innovations must simultaneously address technical viability and cost competitiveness, while awaiting potential policy feedback loops. Notably, breakthrough innovations in renewable hydrogen technologies could trigger institutional adaptation, exemplified by possible subsidy restructuring at the national level following localized adoption of photovoltaic-based hydrogen production driven by carbon credit mechanisms. Conversely, if critical technological breakthroughs (such as non-precious metal catalysts and/or ultra-large-scale electrolyzers in hydrogen production, and non-precious metal catalysts and/or effectively exchange membrane in fuel cells) are delayed, HFCEVs risk being confined to extended policy demonstration phases [26], relegated to being backup-options instead of primary pathways in the energy transition.

6. Breaking Dual Lock-Ins Through DTMLP Framework: Digitally Enabled Dynamic Synergy Pathways for China's Low-Carbon Transport Transition

Building upon the MLP foundation established in prior analyses (Sections 4 and 5), dual institutional-technological lock-ins have been observed as confronting China's transport transition: (1) The binding requirement of 60% carbon intensity reduction by 2035 (IPCC AR6 Baseline Scenario), and (2) strategic mineral dependencies (external dependencies of lithium, cobalt, and nickel exceed 80%) exacerbated by global supply chain restructuring. Through institutional logic analysis, the present section reconceptualizes BEV–HFCEV coordination, not as simple technological complementarity, but as co-evolutionary pathways navigating multi-scalar regime pressures.

6.1. Multi-Level Transition Pathways: Application Landscape, Institutional Evolution, and Technological Synergy

At the landscape layer, BEVs have achieved large-scale application in light-duty vehicles, with a possible penetration rate of 40% in 2024. Their total cost of ownership reached parity with fuel vehicles in 2022, driving an S-shaped market growth curve, while demonstrating a 58.2% emission reduction efficiency in short-distance passenger scenarios. HFCEVs address the limitations of long-haul freight transport, proving essential for heavy-duty trucks, due to their advantages in driving range, payload capacity, and refueling time, with a decarbonization potential of 70%. Substituting hydrogen for diesel could result in a 90% reduction in NO_x emissions, although cost constraints have hindered development. Considering energy security, both BEVs and HFCEVs help mitigate dependence on oil, but they also introduce new vulnerabilities in supply chains, which underscores the urgent need for resource localization and reductions in production costs.

At the regime layer, both BEVs and HFCEVs have undergone policy optimization adaptations influenced by alliance-based coevolutionary dynamics. Since 2018, subsidies for BEVs have declined annually, shifting the focus toward R&D incentives. In contrast, HFCEV subsidies increased annually from 2020 to 2024, amounting to about a thousand dollars per vehicle, although these are linked to green hydrogen production targets that may diminish overall emission effectiveness [114]. Additionally, local governments favor

HFCEVs for fostering regional hydrogen energy development, while the central government emphasizes improving the economies of scale for BEVs, leading to vertical governance conflicts. Market differentiation is becoming more pronounced: the adoption of BEVs follows an S-curve driven by consumer economics, while HFCEVs remain heavily reliant on policies, with 85% of sales concentrated in subsidized urban clusters. Infrastructure gaps and regional disparities pose challenges for both BEVs and HFCEVs, where the coastal charging station density reaches 5.8/km², compared to only 0.05 hydrogen station per 10,000 km². While competition for infrastructure persists, synergies are emerging through pilot projects featuring integrated solar–storage–charging–hydrogen stations and shared maintenance networks in selected regions.

At the niche layer, within the resource allocation framework of renewable energy system integration, LIBs and hydrogen electrolysis technologies demonstrate strategic complementarity. Dynamic energy system modeling reveals that dedicating 30% of wind-solar generation capacity to green hydrogen production could not only mitigate grid congestion pressure from mass BEVs charging but also establish entire life cycle carbon neutrality pathways for HFCEVs. Techno-economic analysis can delineate market segmentation patterns: BEVs dominate urban light-duty mobility through established charging infrastructure and economic advantages, while HFCEVs secure heavy-duty logistics, with extended range and rapid refueling characteristics. Hybrid architecture innovations validate emission reduction synergies from technological convergence, as evidenced by a 8.7% system efficiency improvement in hydrogen-electric bus systems through dynamic coupling mechanisms and multi-objective energy management strategies. Meanwhile, infrastructure co-development and collaborative R&D form critical pathways for systemic integration. A spatial aggregation strategy for charging–swapping–hydrogen refueling stations can enhance operational efficiency and service coverage through shared resources, with Yangtze River Delta pilot data showing more than 30% increased utilization rates in an integrated energy hub. Cross-domain breakthroughs in materials science and AI drive technological convergence: Sulfonated polymer substrates enable simultaneous advancements in solid-state battery electrodes and PEM electrolyzer catalytic layers, while machine learning-based battery health monitoring and hydrogen leakage detection systems establish robust safety frameworks through data interoperability. Such technological synergies can accelerate individual technology maturation and reshape the NEV ecosystem via cross-system optimization.

6.2. Technological Synergy and Systemic Restructuring: Development Pathways and Structural Optimization Strategies for New Energy Vehicles

Within the DTMLP framework, BEVs and HFCEVs exhibit asymmetric development characteristics: BEVs are driven by macro decarbonization targets (landscape-level) yet constrained by fragmented policies (regime-level) and resource limitations (niche-level), while HFCEVs depend on long-term landscape visions but faces institutional inadequacies and cost barriers. A synergistic development pathway can evolve through three phases:

Near-term (2025–2030): BEVs dominate light-duty vehicles (60% penetration) with HFCEVs penetrating heavy-duty truck pilots (15%), focusing on grid–hydrogen coupling;

Mid-term (2030–2045): HFCEVs achieve total cost of ownership parity in logistics, alongside BEVs expansion into medium trucks, with 50% infrastructure co-location;

Long-term (post-2045): HFCV–BEV hybrids prevail, reducing life cycle emissions by more than 40% through circular ecosystems.

Current BEV and HFCEV technologies encounter systemic challenges in achieving immediate decarbonization objectives, primarily attributed to fragmented policy frameworks and imbalanced allocation of technical resources. This predicament necessitates the establishment of transitional mechanisms that synergize technological innovation with transportation struc-

ture optimization. The dual-track strategy of R&D advancement–scenario reconfiguration enables dynamic technological maturation and market compatibility improvements.

Implementing a ‘private-to-public transition’ strategy in passenger transport creates foundational scenarios for scaled NEV applications. By 2022, China’s private passenger vehicle fleet reached 257 million units with an annual carbon intensity of 1.132 tons/person. In contrast, rail transit demonstrates a superior environmental performance, with a per-passenger-km emission intensity of 0.19 kg CO_{2eq} and transport capacity density exceeding road transport by 100 times. The energy transition trajectory from 2020 to 2023 (as illustrated in Figure 13) revealed the continuous market share contraction of conventional fuel vehicles (diesel/gasoline/CNG), while clean technologies including BEVs, PHEVs, and HFCEVs exhibited significant growth momentum, with the PHEV market penetration surpassing 60%. The public transport sector is entering a new low-carbon phase through technological deployments in electric buses and modern trams. Simulations suggest that achieving a 5% annual electrification substitution rate in public transport could yield cumulative emission reductions of 4% by 2030, with amplified efficacy anticipated from increasing clean energy generation, such as Shenzhen’s comprehensive bus electrification initiative, demonstrating that systematic substitution reduced energy consumption and emissions by 73% and 48%, respectively [115]. This structural optimization not only alleviates the grid load pressure from BEVs but expands application scenarios for HFCEVs in intercity transport networks.

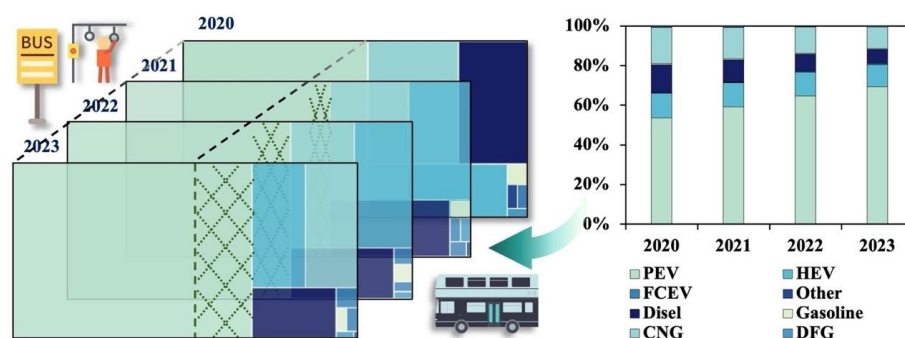


Figure 13. Composition of public buses and trolleybuses from 2020 to 2023 (data from the Ministry of Transport of the People’s Republic of China [116–119]; drawn by the authors).

Nevertheless, the escalating demand for passenger transportation intensifies the complexity of road traffic governance, posing dual challenges to carbon reduction targets. There is significant operational sensitivity in vehicular fuel economy: fuel consumption under low-speed conditions (e.g., less than 30 km/h) can increase by approximately 50% compared to high-speed scenarios (e.g., 80 km/h), with idling emissions during traffic congestion amplifying environmental externalities. In this context, intelligent transportation management systems employing AI-powered vehicle–road coordination algorithms [120,121] could reduce low-speed travel duration, while achieving synchronized decreases of 1–3% in fuel consumption and carbon emissions. Notably, BEVs leveraged high-efficiency regenerative braking systems and congestion mitigation auxiliaries to enhance energy recovery efficiency by 13% under intelligent traffic interventions [122], whereas HFCEVs shortened hydrogen refueling station response times through dynamic dispatch systems. These dual technological pathways synergistically facilitate low-carbon restructuring of multimodal transportation systems.

From a structural perspective, rail transport demonstrates comparative advantages with a 75% electrification rate, substantially outperforming road transportation. Empirical data reveal that rail systems carrying 8% of global passenger traffic and 7% of freight volume consume only 2% of the transportation sector’s total energy [123], exhibiting life

cycle emission intensities 1–2 orders of magnitude lower than road transport [124]. Multi-objective optimization modeling considering carbon emissions, transportation efficiency, and employment effects identified the optimal 2023 freight turnover ratio structure as 14.82:30.06:52.83:0.12:2.17. During 2019–2023, high-speed rail networks contributed 2.3% to emissions reductions in northern urban clusters. Simulations demonstrated that intensifying “rail-for-road substitution” strategies could decrease intercity transport energy consumption by 10% and reduce commercial logistics emissions by 31.4% [125].

Alliance mechanisms accelerate structural optimization through policy instrument portfolios, encompassing legislative safeguards, digital governance, fiscal subsidies, and spatial planning. Representative cases include ‘Carbon Account’ systems converting public transit usage into emission reduction incentives and infrastructure supply-side reforms, enhancing integrated transport hub efficiency. Crucially, structural optimization complements rather than replaces technological innovation. Through tri-dimensional interventions of ‘transit priority + spatial reorganization + digital governance’, secondary growth curves can be established during phases of diminishing marginal technological returns. According to innovation diffusion dynamic models [126], as NEV market penetration approaches the S-curve inflection point, this synergistic mechanism can secure strategic windows for breakthrough innovations in long-cycle technologies like power batteries and hydrogen energy.

7. Development Roadmap for the Transformation of Low-Carbon Road Transport in China: Future Perspectives

Based on the analysis of policy evolution, technological advancement, and emission reduction effects using the DTMLP, a three-phase decarbonization pathway for China’s road transport sector from 2025 to 2050 has been proposed, as demonstrated in Figure 14. This roadmap conceptualizes the transition as a progressive ‘pressure transmission–technological adaptation–system transition’ model, with stage-specific green development objectives and implementation strategies that dynamically respond to technological maturity and contextual challenges.

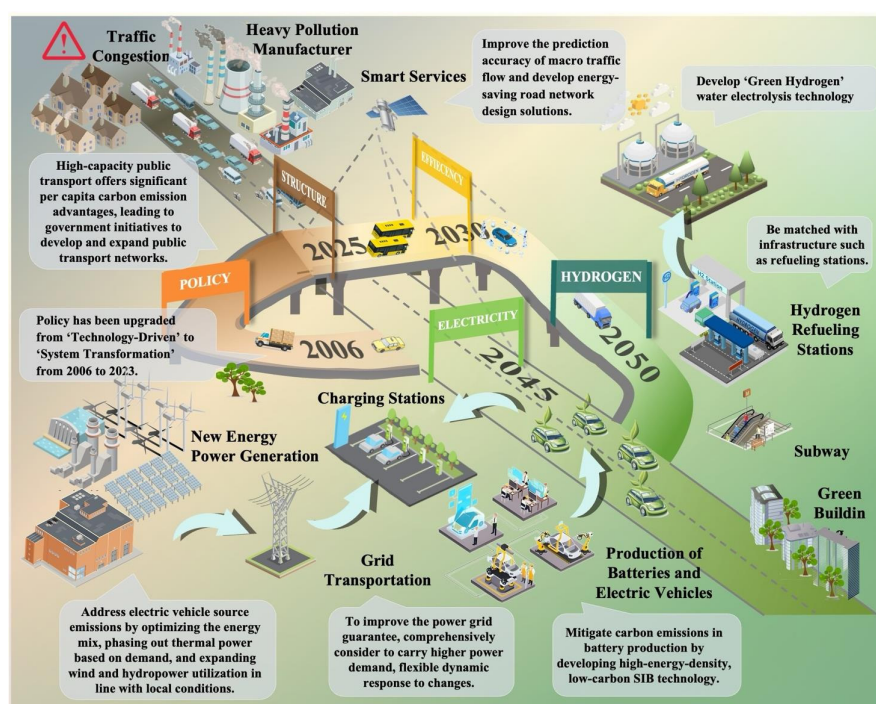


Figure 14. Analytical framework for the low-carbon transformation of China’s road transport sector.

1. Short-term Pressure Transmission Phase (2025–2030)

Emission reduction primarily relies on structural optimization rather than technological breakthroughs. Implementing multimodal ‘road-to-rail/water’ systems (achieving 5% annual substitution rate) could deliver 4% baseline emission reduction, with efficacy amplification tied to clean energy generation growth. Empirical evidence shows that a 10% increase in rail network density reduces urban transport emission intensity by 1.0–1.5%. Key initiatives include

- Developing rail-dominated mobility systems through intercity high-speed rail, regional express rails, and intelligent bus networks, projecting a 2.3% emission reduction contribution in northern megacities;
- Deploying AI-5G integrated dynamic traffic management systems, reducing low-speed travel duration by 11% through peak-hour vehicle–road coordination, concurrently decreasing fuel consumption and emissions by 3–7%;
- Enhancing BEV smart energy management could boost regenerative braking efficiency by 25% in congested conditions, while reducing HFCEV refueling station response time by 18%.

2. Medium-term Technological Adaptation Phase (2030–2045)

This phase requires establishing life cycle carbon governance systems to overcome EV technological barriers. Studies indicate that BEVs can reduce per-kilometer emissions by 58.2% versus ICEVs, yet battery materials (particularly cathodes) account for 45% of life cycle emissions. Strategic priorities include

- Advancing high-nickel low-cobalt cathode materials to achieve $1.5\times$ energy density improvement by 2035;
- Developing SIB technology targeting a 400 Wh/kg energy density by 2045, reducing battery production emissions by 70%;
- Constructing renewable-dominated power systems with clean energy shares exceeding 50%/80% by 2035/2045, enabling full electrification potential.

3. Long-term System Transition Phase (post-2045)

Hydrogen emerges as the strategic solution for heavy-duty transport decarbonization. The transition pathway features

- Application gradient expansion: Fuel cell heavy truck penetration surpassing 70% by 2045, reaching 15% in light vehicles by 2050;
- Hydrogen source greening: Renewable electrolysis (green hydrogen) increasing from 30% (2035) to 80% (2050);
- Infrastructure networking: Hydrogen stations reaching 30% of current petrol station density, coupled with gray hydrogen CCS systems. Projections indicate a 65–72% reduction in intercity freight emission intensity through hydrogen adoption.

8. Conclusions

Employing the DTMLP analytical framework, this study systematically deciphered the evolutionary logic of China’s low-carbon road transport policies and technological transition pathways since 2006, yielding key findings:

1. Policy Paradigm Shift: From Technological Drive to Institutional Reform.

The dual forces of ‘dual-carbon’ targets and evolving socio-economic demands catalyzed a paradigm shift in policy logic from the 11th to 14th Five-Year Plans. Innovative policy instruments, including blockchain-enabled cross-border carbon tracking (addressing logistics emissions) and AI-optimized carbon inclusion mechanisms (mitigating congestion

emissions) established a central–local governance system balancing strategic consistency and regional heterogeneity. Institutional analysis revealed that digital carbon accounting systems in manufacturing clusters can reduce logistics emission intensity by 18–22%, while megacity intelligent traffic interventions can decrease congestion emissions by 12–15%.

2. BEV Technological Dilemmas and Breakthrough Pathways.

Despite landscape-level promotion, BEV emission reduction faces triple lock-in effects: (i) institutional fragmentation, causing 23–28% technology diffusion efficiency loss; (ii) carbon lock-in in battery production (45% of life cycle emissions); and (iii) power structure carbon lock-in (>60% coal-based), with the solution lying in a synergistic innovation system integrating green power, sodium resource substitution, and vehicle–grid integration, projected to reduce BEV life cycle carbon intensity by 52–58%.

3. HFCEV Development Barriers and Transition Thresholds.

While HFCEVs possess the potential to overcome EV range limitations, they confront the following issues: (i) structural contradiction between strategic vision and institutional support; (ii) grey hydrogen dominance (>80%), constraining carbon benefits; and (iii) technological gaps in storage/refueling compared to international benchmarks, which requires significant improvements in electrolyzer efficiency, hydrogen station density, and green hydrogen cost for a marketization with practical significance.

4. Three-Phase Transition Pathway Design.

Proposing a stepped ‘structural optimization–power transition–hydrogen synergy’ roadmap: (i) the short-term (2025–2030) focuses on achieving 4–6% emission reductions through multimodal restructuring, while establishing AI-5G intelligent traffic management; (ii) the medium-term (2030–2045) focuses on advancing high-energy-density battery technologies supported by renewable energy grids; and (iii) the long-term (2045–2050) focuses on constructing hydrogen–electricity networks for heavy-duty decarbonization and establishing a systemic governance framework encompassing multiple elements.

5. Limitations and Future Research

This study has limitations that warrant further investigation. First, the DTMLP framework simplifies actor interactions, such as shifts in consumer behavior, which were not fully quantified and should be considered in future analyses. Second, the analysis predominantly relied on aggregated national data and case studies from developed urban clusters, potentially overlooking the unique challenges of rural and less-developed regions in adopting low-carbon transport technologies. Future research should incorporate granular regional datasets to evaluate spatial disparities in infrastructure deployment and policy effectiveness.

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