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Sustainable Roadmap for China's Low-Carbon Road Transportation: From Policy to Practice

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Abstract: The road transport sector in China is confronted with the dual challenges of escalating demand and the critical need to mitigate greenhouse gas emissions. This situation necessitates urgently formulating a precise and comprehensive low-carbon development framework congruent with the objectives outlined in the Paris Agreement. By synthesizing pertinent national and regional policies, this analysis underscores the pivotal role of governmental interventions in promoting innovation and facilitating investment in low-carbon technologies. We propose a series of strategic public interventions essential for transitioning to low-carbon transportation systems within the forthcoming five-year period. These are anticipated to effectively counterbalance the anticipated rise in carbon emissions triggered by increasing demand. Furthermore,the present analysis encompasses a comparative assessment of various transportation technologies' benefits, drawbacks, and obstacles. This assessment focuses mainly on the developmental maturity of these technologies and the low-carbon potential inherent in electric and fuel-cell vehicles. Ultimately, this study delineates a strategic roadmap for establishing a resilient low-carbon transport system, contributing to the broader discourse on sustainable transportation. It also provides actionable recommendations for policymakers and stakeholders dedicated to fostering a greener future.

Keywords: China; road transportation sector; low-carbon development; battery vehicles; hydrogen fuel cell vehicles; policy path

1. Introduction

Climate change presents a substantial challenge to the global community, impacting vulnerable populations and ecosystems [1], with human activities driving carbon emissions. In response, nations have committed to the Paris Agreement, endeavoring to enhance their Nationally Determined Contributions (NDCs) to tackle this urgent issue [2]. Each industry requires tailored emission reduction strategies, and the transportation sector is a crucial focus for many countries' NDCs since it accounts for approximately 26% of carbon emissions [3]. Road transport features a large user base, high emissions output, diverse sources, and notable mitigation opportunities [4–6]. Additionally, progress in carbon 2 reduction technologies parallels advancements in aviation and maritime industries, highlighting its importance for environmental sustainability. China's transport sector is the third-largest carbon emitter after power and industry [7] and globally ranks third behind the US and EU. Road freight and passenger traffic are expected to grow by 2% and 3.2% annually over five

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years [8], raising emissions. The World Resources Institute [9] states emissions must peak between 2025 and 2035 for China to reach carbon neutrality by 2060. Over 50% of road freight emissions come from passenger and freight vehicles [3].Therefore, advancing low-carbon development in China's transportation sector, especially road transport, is vital for global sustainability.

Recently, China has introduced various policies to promote sustainable road transportation. These initiatives include technology-driven strategies such as hybrid technologies, advanced internal combustion engines, high-performance transmissions, electronics, and lightweight materials. Outcomes are promising; projections for 2023 estimate that new energy vehicle penetration in China will reach 31.6%, with emissions reductions totaling 80 million tons. Establishing a charging infrastructure network is expected to grow by 51.7%, accelerating new energy vehicle development. By 2035,market penetration for new energy vehicles is projected to hit 90%,with over 200 million vehicles expected. The hydrogen fuel cell market for commercial vehicles and buses has expanded, leading to a 19.6% increase in hydrogen refueling stations. The 2022 Beijing Winter Olympics showcased the world's most significant carbon-neutral fuel cell vehicle application. Public transport systems are vital to the city's net-zero goals [3], potentially achieving a 40.28% carbon reduction when integrated with natural gas or electrification [10].

In the modern automotive market, various electrified vehicles—battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), range-extended electric vehicles (REEVs), and fuel cell vehicles (FCVs)—will coexist for an extended period to reduce carbon emissions per vehicle significantly. However, a gap remains between these vehicle types and large-scale carbon reduction goals. As demonstrated in Figure 1, new energy vehicles in China (2018-2022) have not yet dominated the market, facing barriers such as resource conflicts [11], dependence on core materials [12],slow technological advances [13], high emission reduction costs [14], insufficient infrastructure [15], and economic andsocial acceptance [16]. High hydrogen fuel costs and carbon intensity of grey hydrogen limit FCV market share in the short term [17], and the shift of environmental impact from usage to battery production and power supply creates uncertainty in the potential of carbon reduction for electrified vehicles [18]. Developing a robust transportation system integrating various vehicle power technologies, adaptable matching processes, phased coordination, and diverse transportation policies is necessary and urgent. However, current development plans need more clarity and comprehensiveness regarding trajectories.

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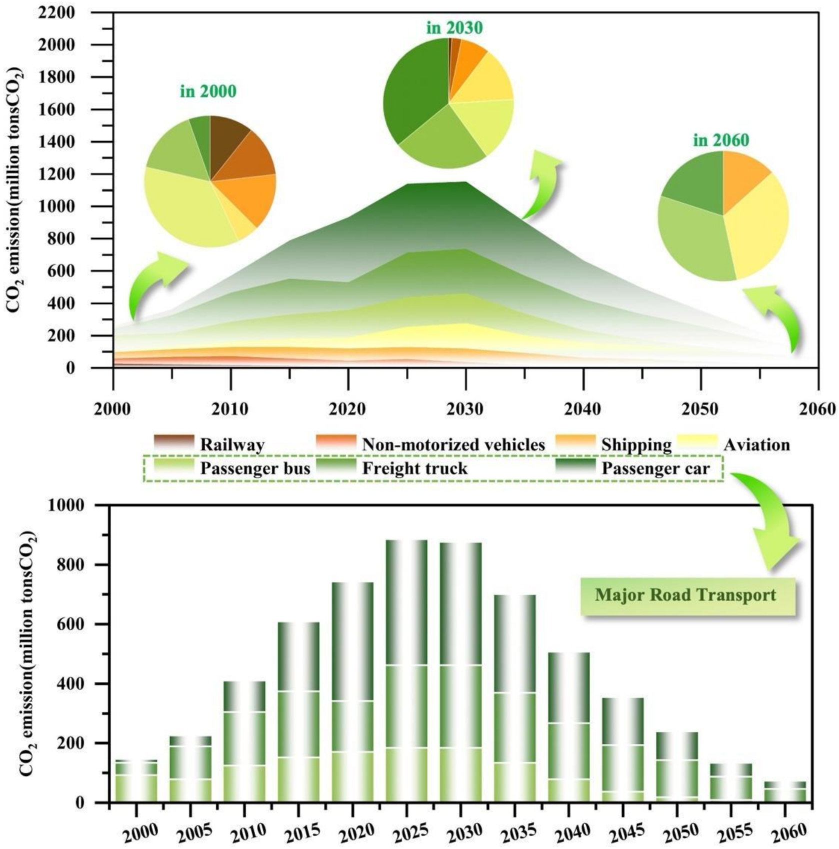

Figure 1. Carbon emissions contributed by the transportation sector, together with the three primary sources of highways 2000-2060.

This article proposes a pragmatic and viable development strategy to facilitate the low-carbon advancement of China's road transportation sector. It analyzes various transportation technologies' advantages, disadvantages, and challenges by comparing future development forecasts based on singular technologies or application scenarios. Additionally, the article evaluates the environmental impacts of these technologies throughout their lifecycle. The analysis will be guided by addressing the following research questions:

1) How can short-term decarbonization pressures from existing technology limitations be mitigated?

2) How can the carbon emissions attributable to the operational phase of electric vehicles be effectively reduced?

3) What technical challenges are encountered in developing hydrogenation technologies for vehicles?

4) How can policymakers create a rational path for energy conservation and emissions based on technological maturity and development stages reduction?

2. An Examination of China's Current Low-Carbon Emission Reduction Policies for the Road Transport Sector

2.1. Relevant Policies at the Central Government Level

As listed in Table.1, throughout various economic and social development stages, China's approach to enhancing low-carbon emission reduction policies within the transportation sector has evolved progressively, reflecting a commitment to sustainable development and international cooperation.

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Table 1. Energy conservation and emission reduction policies in China's road transportation sector (as of October 2024).

Time	Policy Act	Concrete Concept
2006 (March)	Outline of 11th Five-Year Plan for National Economic and Social Development	✧ 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 combat climate change effectively.
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)	Determine the Energy Conservation and Emission Reduction targets of the Transportation Industry during 11th Five-Year Plan	✧ 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 the Demonstration and 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.
2011 (June)	Outline of 12th Five-Year Plan for National Economic and Social Development	✧ 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	✧ 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 the Pilot Work of Recycling and Utilization of Power Batteries for New Energy Vehicles	✧ Advocate recycling new energy vehicle batteries by establishing a service network. Enhance initiatives with consumer incentives like repurchase programs and battery

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		exchanges. This tackles environmental concerns and promotes sustainability, aligning with our commitment to a greener future.
2019 (April)	Opinions on Accelerating the Transformation and Upgrading of the Road Freight Transport and Promoting 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 impact. Implement differentiated tolls on expressways to incentivize low-emission transport and foster sustainable logistics solutions.
2020 (December)	China's Energy Development in the 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)	National Comprehensive Planning Outline of Transportation Network	✧ 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)	Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Fuel and Faithful Implementation of 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)	Modern Comprehensive Transportation System for 14th Five-Year Plan	✧ 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.
2021 (November)	Opinions on Deeply Fighting the War on 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 the Development of Multimodal Transport and	✧ Advocate for shifting bulk materials to rail and waterways, highlighting combined transport benefits for iron and water. Exploring

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	Optimizing and Adjusting Transport Structure (2021-2025)	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 Planform Accelerating the Construction of a Powerful 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)	China Pledges to Promote Renewable Energy Use Amid Green Transition	✧ 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 by implementing energy conservation and fuel substitution measures. The government has established specific energy conservation and emission reduction targets while promoting market-oriented reforms. Nonetheless, there has been a pronounced emphasis on reducing energy intensity and diversifying energy sources to ensure the safe utilization of energy resources [19]. Implementing the 13th Five-Year Plan (2016-2020) marked the commencement of a new era. The government has shifted significantly toward facilitating the profound integration of advanced intelligent technologies with energy systems and transportation sectors. Since 2020, the central government has established a ' 1+N ' carbon peak and carbon neutrality policy framework [20], in which the term ' 1 ' signifies the paramount commitment to achieving carbon peak and carbon neutrality, serving as a pivotal role in guiding governmental efforts, while 'N ' denotes the specific implementation strategies tailored to various regions, sectors, and industries.

This framework has prominently highlighted the concepts of green transportation and low-carbon transformation, signifying a paradigm shift in policies from focusing on *Technology Promotion to System Transformation*. Furthermore, the government underscores the necessity for comprehensive advancement in green and low-carbon transformation of road transportation. This encompasses multifaceted strategies, including policy guidance, technical support, market mechanisms, and infrastructure development, promoting synergistic development across disparate fields and articulating a more coherent and coordinated future trajectory.

2.2. Relevant Policies at the Megacities

In China's decentralized governance, local governments enact central economic, environmental, and climate policies[21]. The diverse development of megacities and medium and small cities necessitates tailored regional measures in line with central directives, focusing on problem analysis and implementation. In densely populated megacities, transportation emissions reduction is crucial [22,23], impacting public health and governance. Nonetheless, urban advancements provide models for energy efficiency and emissions reduction, supported by pilot programs. This section will analyze relevant policies.

Beijing, China's capital, struggles with traffic congestion and high air pollution levels. Since hosting the Olympics in 2008, Beijing has enhanced public transportation and promoted sustainable travel. Initiatives to cut vehicular pollution and support low-carbon transport have also been implemented. Beijing's 14th five-year plan for transportation development, launched in 2020, aims to

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modernize the system with green principles, tackling congestion to improve air quality. Meanwhile, Beijing's green travel model has shifted to market strategies like carbon trading and optimized road use redistribution.

Table 2. Beijing Road traffic energy conservation and emission reduction policies sorting out (as of October 2024).

Time	Policy Act	Concrete Concept
2006 (September)	Beijing's Plan for Energy Conservation and Climate Change during the Period of 11th Five-Year Plan	✧ Promote urban public transport and eco-friendly vehicles while removing high-energy, high-emission ones. Support fuel-saving technologies like additives and alternative fuels. Improve the Beijing road layout and intersections to enhance traffic efficiency and reduce congestion.
2009 (July)	Beijing Action Plan for Building Humanistic Transportation, Technology and Green Transportation (2009-2015)	✧ Promote energy conservation and low-emission vehicles while guiding travel habits. By 2015, aim to have a transportation system for 45% of trips and 50% during peak hours. Plans include 13 passenger hubs, 50 transfer stations, bike lane expansion, rentals, accessibility improvements, and 50,000 green logistics vehicles. Encourage green travel through buses, cycling, and walking.
2011 (December)	Energy Conservation, Consumption Reduction and Climate Change Plan of Beijing during the 12th Five-Year Plan Period	✧ Prioritize public transport for 50% usage in central areas by 2015. Accelerate rail construction to 660 kilometers and establish 1,000 bike rental stations for 50,000 vehicles. Improve the microcirculation network to tackle the "last kilometer" issue and boost traffic efficiency.
2013 (September)	Beijing Released a Five-Year Clean Air Action Plan (2013-2017)	✧ Reduce vehicle emissions, optimize traffic, enhance public transport, and promote new energy vehicles to improve air quality.
2014 (March)	Regulations on Beijing Municipal Prevention and Control of Air Pollution	✧ The vehicle emission standards have been clarified, the supervision of vehicle emissions has been strengthened, the progress of vehicle emission control technology has been promoted, and the development of green transportation has been promoted.
2015 (December)	The Energy Development Plan of Beijing Municipality during the 13th Five-Year Plan Period	✧ Create a green, low-carbon transport system and improve urban energy structures. By 2020, gasoline and diesel use will decrease by 15%, with stable yet declining carbon emissions in transport.
2016 (June)	Administrative Measures for The Promotion and Application of New Energy Vehicles in Beijing Municipality	✧ Encourage standardization of new energy vehicle use, such as electric and plug-in hybrid vehicles, to lower emissions and enhance energy conservation in transportation.
2019 (July)	Benchmark of Discretion of Administrative Examination and Approval Items for Motor Vehicle models and Non-road Mobile	✧ Specific requirements are put forward for the emission pollution prevention and control of motor vehicles and non-road mobile machinery, the supervision of motor vehicle emission is strengthened, the progress of motor vehicle

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	Machinery Meeting the Prescribed Emission and Energy Consumption Standards in Beijing	emission control technology is promoted, and the development of green traffic is promoted.
2021 (December)	Energy Development Plan of Beijing Municipality during the Period of 14th Five-Year Plan	✧ Develop a green, low-carbon transportation system and optimize urban transport and energy structures. By 2025, gasoline and diesel use will drop by 20% from the peak, stabilizing and reducing carbon emissions in transportation.
2022 (April)	Beiling Transportation Development and Construction Plan during the Period of 14th Five-Year Plan	✧ Encourage energy consumption changes in transportation and speed the green transformation. We'll support low-carbon and new energy vehicles across public transport, rental, tourism, and freight sectors. During the 14th Five-Year Plan, we'll create a modern, comprehensive, green, safe, intelligent urban transportation system.
2022 (April)	The Action Plan for Comprehensive Transportation Management in Beijing in 2022	✧ By 2022, urban transportation will significantly improve. Green travel in central areas will hit 74.6%, with 56% of commutes under 45 minutes. Rail and bus transfers will optimize to 30 meters, and peak traffic will be effectively managed. Future plans will prioritize "people-oriented" concepts, focusing on slow transportation and buses while integrating innovative traffic management to enhance quality and efficiency.
2022 (July)	Low-carbon design standard for Urban Comprehensive Passenger Transfer Hub	✧ Complete the application of low-carbon technology for the new construction, expansion and reconstruction of urban comprehensive passenger transportation
2022 (October)	Implementation Plan of Beijing Carbon Peak	✧ Innovate regional low-carbon cooperation mechanisms and work together to promote carbon peak and carbon neutrality. We will promote the low-carbon energy transformation in the Beijing-Tianjin-Hebei region, and vigorously develop regional wind power, photovoltaic and green hydrogen resources
2024 (March)	The Beijing Municipal Comprehensive Transportation Management Action Plan for 2024	✧ Advocate for green travel and new energy vehicles. We will enhance publicity for green travel, optimize vehicle energy structures, and support the new energy vehicle plan. This includes promoting electric taxis and phasing out diesel trucks that don't meet national IV standards. Additionally, we will improve charging infrastructure and equipment at transportation hubs, stations, and highways.

Shanghai, China's economic center, has a dense and complex multi-level transportation structure [24]. In the development of new energy vehicles, 12th and 13th Five-Year Plans have been concerned with the application of solar energy in transportation infrastructure to ensure the development of the new energy vehicle industry, as listed in Table 3, from the initial goal orientation to the construction of charging facilities, and then to the promotion of industrialization, is the

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advanced technology development pilot area. Since the 14th Five-Year Plan, Shanghai has focused on achieving green, low-carbon transformation and developing intelligent transportation systems.

Table 3. Shanghai Road traffic energy conservation and emission reduction policies sorting out (as of October 2024).

Time	Policy Act	Concrete Concept
2012	Shanghai's 12th Five-Year Plan for Energy Conservation and Emission Reduction	✧ Improve the energy efficiency of transportation, reduce carbon dioxide emissions, promote the construction of ETC system, develop solar energy applications, and promote highway transportation.
2013	Shanghai Municipal Clean Air Action Plan (2013-2017)	✧ Optimize the traffic structure, reduce the dependence on private cars, promote new energy vehicles, control the number of motor vehicles, and use low-sulfur oil on port ships.
2014	Implementation plan for Promotion and Application of New Energy Vehicles in Shanghai Municipality	✧ Promote 13,000 new energy vehicles, build charging facilities, and promote the development of the new energy vehicle industry.
2016	Shanghai Municipal Comprehensive Transportation (13th Five-Year Plan)	✧ Develop green ports, promote new-energy vehicles, build charging facilities, improve slow traffic, and improve the energy efficiency of transportation vehicles.
2017	Measures of Shanghai Municipality for the Administration of Special Funds for Transportation Energy Conservation and Emission Reduction	✧ Special funds will be set up to support projects involving new energy vehicles and charging facilities.
2018	Shanghai Municipal Clean Air Action Plan (2018-2022)	✧ Increase the proportion of green travel, promote the replacement of electric buses, implement stricter emission standards, and eliminate high-polluting vehicles.
2019	Shanghai City Promotes the Adjustment Implementation Plan of Transportation Structure	✧ Promote green freight transport, new energy distribution vehicles, increase charging piles, and improve the information level of multimodal transport.
2019	Action Plan for Energy Conservation and Consumption Reduction in Shanghai Transportation Industry	✧ Improve the energy efficiency of transport vehicles, optimize the transport structure, and promote energy-saving technologies.
2020	Shanghai Transportation Industry Action Plan on Climate Change	✧ Improve energy efficiency, reduce greenhouse gas emissions, and promote low-carbon transportation modes.
2020 (May)	Key Work Arrangement for Energy Conservation and Emission Reduction in Shanghai Transportation Industry in 2020	✧ Promote energy-saving technologies, strengthen driving skills training, and promote technological innovation.
2021 (February)	Shanghai Municipality's Implementation Plan to	✧ Develop new energy vehicles, with an annual output of 1.2 million vehicles,

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	Accelerate the Development of New Energy Vehicle Industry	electrification the public sector, and promote the construction of intelligent transportation systems.
2021 (June)	14th Five-Year Plan for the Comprehensive Transportation Development of Shanghai Municipality	✧ Improved the comprehensive transportation system, developed green transportation models, and improved the level of intelligent transportation. The proportion of public transportation trips reached 45%.
2021 (July)	Key Work Arrangements for Energy Conservation, Emission Reduction and Climate Change Response in Shanghai	✧ Promote key energy-saving and low-carbon projects, improve the energy efficiency of data centers, and support new energy projects.
2022 (June)	Measures of Shanghai Municipality on the Management of Special Support Funds for Transportation Energy Conservation and Emission Reduction	✧ Support energy conservation and emission reduction projects and encourage the application of new technologies and clean energy.
2022 (October)	White Paper on Shanghai Traffic Development	✧ Reduce the impact of traffic ecological environment and promote traffic carbon peak and carbon neutral.
2022 (October)	Implementation Plan for Energy Conservation and Emission Reduction during the Period of 14th Five-Year Plan	✧ Promote green, low-carbon and circular development, and help achieve carbon peak and carbon neutrality.
2023 (January)	Implementation Plan of carbon peak in Shanghai transportation field	✧ Reduce energy consumption throughout the life cycle, promote the construction of green roads, and upgrade transportation infrastructure.
2023 (June)	Implementation Plan of Photovoltaic Promotion and Application in Shanghai Transportation Field	✧ By 2025,120MW of installed photovoltaic capacity will be added, promoting the full coverage of rooftop photovoltaic in transportation facilities.
2023 (July)	Shanghai Municipal Clean Air Action Plan (2023-2025)	✧ Promote the "public rail" and "public water", promote new energy vehicles, and strengthen green development in ports and aviation.
2023 (September)	Administrative Measures of Shanghai Municipality for Carbon Universal Benefit (Trial)	✧ Establish a carbon inclusive system and promote green and low-carbon production and lifestyle.
2023 (September)	Shanghai to Enliven the Automobile Circulation and Expand the Automobile-Renewal Consumption Measures	✧ Provide subsidies for car purchases to promote the consumption of new energy vehicles and second-hand car transactions.
2023 (September)	Plan for Eco-Green Integrated Development of Yangtze Delta	✧ Build a green and low-carbon transportation system and promote green travel to reach 80 percent.

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2024 (September)	Shanghai Municipality's Action Plan for Accelerating Green and Low-Carbon Transformation	✧ Improve the public and pedestrian transportation systems and increase the proportion of green travel in central urban areas to 75 percent.

Guangdong, China's largest province by economy, proposed measures in 2007 to enhance energy conservation and cut transportation emissions, promote public transport and clean energy vehicles, and phase out high-emission vehicles. In the 2010s, the policies (as listed in Table 4) focused on optimizing the transportation system, with more precise goals set in 2014 for combining different transport modes to boost energy efficiency and environmental standards. During the 13th Five-Year Plan, efforts shifted toward optimizing transportation structure and enhancing green transformation across the system to support sustainable transport development. Guangdong transitioned from technology promotion to systemic structural adjustment, evolving from energy reduction targets to a holistic low-carbon transport system.

Table 4. Guangdong Road traffic energy conservation and emission reduction policies sorting out (as of October 2024).

Time	Policy Act	Concrete Concept
2007	Comprehensive Work Plan for Energy Conservation and Emission Reduction in Guangdong Province	✧ Enhance energy conservation and reduce emissions by prioritizing public transport and efficient bus and rail systems. Limit high fuel consumption vehicles, support eco-friendly production, and phase out old cars. Encourage clean fuels like LPG and LNG, promote new energy vehicles, and enforce regulations. Strengthen fuel standards to eliminate substandard cars and promote GPS for better road coordination.
2011 (July)	Implementation Opinions on Building a Low-carbon Transportation System in The Transportation Industry of Guangdong Province	✧ By 2015, the province's transportation industry has reduced the greenhouse gas emission intensity more effectively, and the industry's awareness of energy conservation and emission reduction has been further enhanced.
2011 (August)	Implementation Opinions on Building a Low-carbon Transportation System in The Transportation Industry of Guangdong Province	✧ Boost alternative energy in transport, apply conservation and emission-reducing technologies in tunnels, and implement energy-saving solutions like smart ventilation and lighting control.
2012 (March)	Comprehensive Work Plan for Energy Conservation and Emission Reduction of Guangdong Province during the 12th Five-Year Plan	✧ Promote energy conservation and emissions reduction in transportation by optimizing resources, enhancing efficiency, and reducing energy use. Develop smart transport systems, improve rail and public transit, and support highways. Enforce fuel consumption standards and limit new buses. Restrict high-emission vehicles and set up low-emission zones. Improve oil quality, targeting Guangdong V gasoline by 2015, and ensure supply of Guangdong IV gasoline and diesel.

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2013	Development Plan of New Energy Automobile Industry of Guangdong Province (2013-2020)	Strengthen environmental management and explore vehicle number control in major cities. ✧ Build a green transportation system, promote energy-saving and new-energy vehicles, improve transportation efficiency, and reduce energy consumption and pollution emissions.
2014 (October)	Notice of General Office of Guangdong Provincial People's Government on Issuing the Action Plan for Energy Conservation, Emission-Reduction, and Low-carbon Development for 2014-2015	✧ Increase locomotive emission reduction, implement five-stage emission standards, accelerate the construction of a comprehensive transportation system, and give full play to the comparative advantages, combined efficiency and comprehensive advantages of various transportation modes such as water, road, iron and air.
2016	Implementation Opinions of The General Office of the Guangdong Provincial People's Government on Accelerating the Promotion and Application of New Energy Vehicles	✧ Special funds will be set up to support the promotion and application of new energy vehicles, including purchase subsidies and the construction of charging infrastructure.
2018	Implementation Plan of Guangdong Province to Win the Battle of Blue Sky Protection (2018-2020)	✧ Strengthen the prevention and control of motor vehicle pollution, promote the use of clean energy vehicles, optimize the traffic structure, and reduce motor vehicle pollution emissions.
2019	Implementation Plan of the Three-year Action Plan for Promoting Transport Structure Adjustment in Guangdong Province	✧ Promote the transport of bulk goods to rail and water transport, optimize the transport structure, improve overall transport efficiency, and reduce pollution from road transport.
2020	Implementation Plan for Energy Conservation and Emission Reduction during the 14th Five-Year Plan Period	✧ The energy conservation and emission reduction targets in transportation for the 14th Five-Year Plan include promoting new energy vehicles and optimizing the transportation structure.
2022 (January)	14th Five-Year Development Plan of Comprehensive Transportation System in Guangdong Province	✧ Enhance infrastructure layout and strategic support capacity. Integrate transport services to improve efficiency. Emphasize smart, green, safe transportation for quality development. Increase support for major projects to ensure plan implementation. During the 14th Five-year Plan, the province invested about 2 trillion yuan in key transportation projects.
2022 (June)	Implementation plan of carbon peak in Guangdong Province	✧ Strengthen energy conservation and carbon reduction in key energy-using units, carry out projects for energy conservation and carbon reduction in cities, upgrade energy conservation in buildings, transportation,

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		lighting, heating and other infrastructure, and improve overall energy efficiency in cities.
2022 (September)	Guangdong Province's implementation plan for energy conservation and emission reduction during 14th Five-Year Plan	✧ Advance green, low-carbon transport through planning, design, construction, and maintenance of infrastructure projects, enhancing charging, gas, hydrogenation, and shore power facilities at ports and airports.
2023 (August)	Implementation Plan of Supporting carbon Trading in Guangdong Province (2023-2030)	✧ Expand carbon market coverage to textiles, ceramics, data centers, transportation, and construction, addressing the EU carbon tariff while managing emissions. Lower entry thresholds for high energy and emission projects and consider including non-CO2 greenhouse gases like methane, nitrous oxide, and sulfur hexafluoride. Establish relevant accounting technologies and reporting systems.
2024 (September)	Guangdong vigorously promoting the green and low-carbon development of transportation	✧ Accelerate transportation structure optimization, deepen multimodal transportation projects, promote low-carbon transformation of tools, renew large-scale equipment, and enhance green infrastructure while focusing on energy conservation and emissions reduction.

3. Potential of in-Depth Optimization of Transportation Structure for Carbon Reduction and Emission Reduction of Road Transportation

3.1. 'Private-to-Public' in the Field of Passenger Transport

According to data presented in China's Statistical Yearbook, the automotive industry has matured progressively since 2013 to accommodate the rapid advancement of the economy and urbanization. As demonstrated in Figure 2, this has led to the emergence of sustainable development practices. Furthermore, there has been a significant increase in the growth rate of new energy vehicle production; however, the production proportion of these vehicles remains below 25%.

From 1978 to 2022, road construction mileage in China grew parabolically, mirroring car ownership increases but outpacing new energy vehicle growth. By the end of 2022, private passenger vehicles totaled around 256.622 million, primarily small cars, emitting 4 million tons of CO_2, equating to 1.132 tons per person. In contrast, public transport, including buses and trams, accounted for less than 1% of total vehicles and emitted under 2 million tons of CO_2. Although public transport has a lower total emission, its unit passenger emissions stood at 1.036 tons of CO_2 per person, putting it at a disadvantage. With urban residents making about 62 public transport trips annually in 2020, per capita emissions were 50 times lower than for private vehicles. Rail transit further enhances low-carbon benefits, having a carrying capacity 100 times greater than road traffic.

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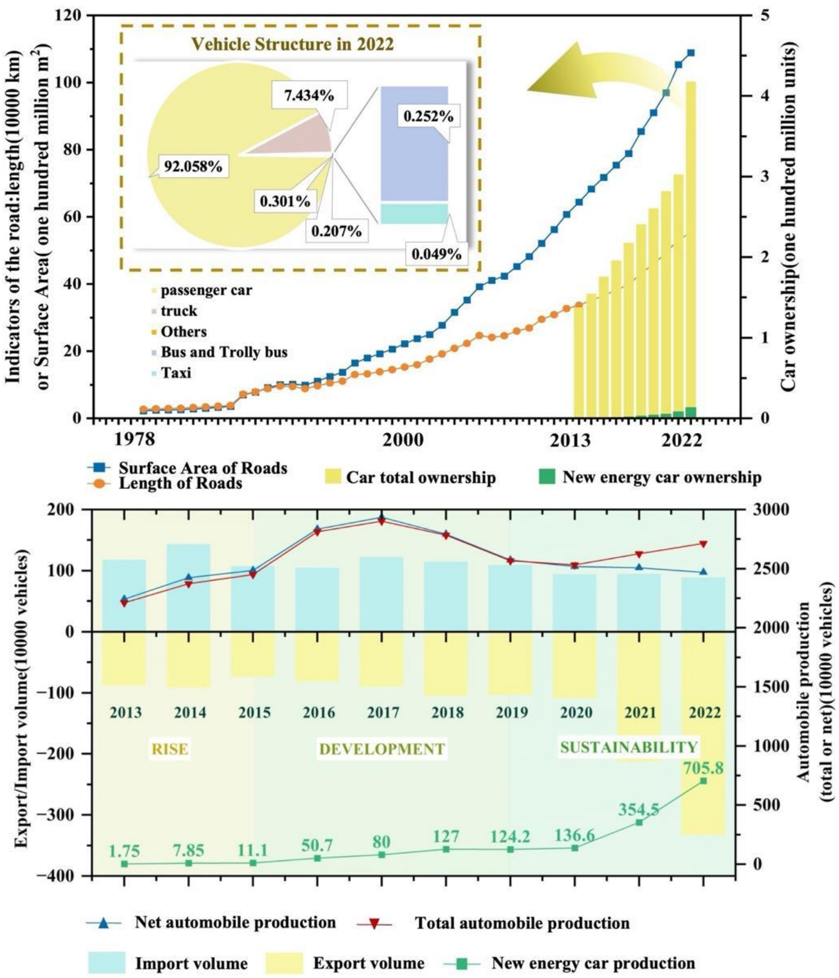

Figure 2. Growth of road mileage and geographical area from 1978 to 2022, alongside the proportion of road vehicles in 2022, together with production and import of vehicles.

This relates to the electrification of public transport vehicles, as Figure 3 demonstrates a shift in energy usage from 2020 to 2023. The proportion of vehicles using traditional energy sources—like diesel, gasoline, and CNG—has declined. The market is shifting from conventional sources to clean energy, with new technologies such as BEVs, PHEVs, and FCVs significantly increasing. By 2023, PHEVs will account for over 60%. The public transport industry is entering a new phase, with low-carbon technologies being applied in buses and trams. For example, Shenzhen has fully electrified its buses, reducing energy consumption by 73% and carbon emissions by 48% [25].

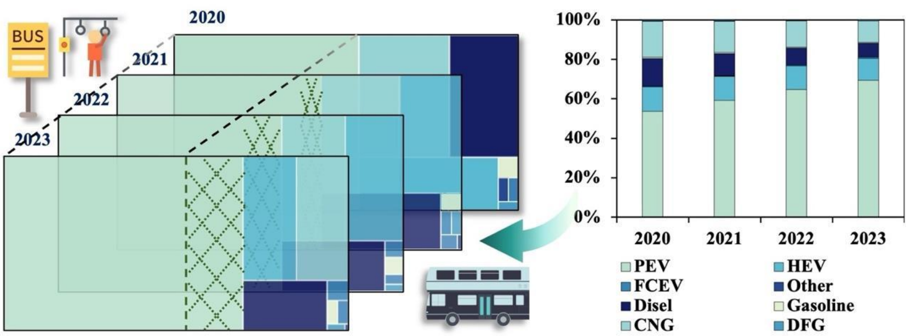

Figure 3. Composition of public buses and trolleybuses from 2020 to 2023 (Data from the Ministry of Transport of the People's Republic of China [26–29]; Draw by the authors).

Given that the electricity utilized for BEVs is predominantly sourced from conventional thermal power grids, it is necessary to analyze the implications of this reliance on fossil fuel-based energy systems is pertinent. In the context of the current thermal power generation proportion in China, based upon the unit energy consumption of various vehicles(including conventional internal combustion engine vehicles, new energy vehicles, and mass transit options such as buses and trams) and the average carbon dioxide emission factor of China's electric power in 2021 (0.5568 kg CO_2/kWh)associated with the existing proportions of each vehicle category, the assessments of emissions per kilometer are respectively 0.19 kg CO_2/km, 0.4343 kg CO_2/km, and 0.1836 kg CO_2/km for subway systems, buses and/or trams, and private passenger vehicles. Moreover, in consideration of the assumed carrying capacity ratios among various transport modes—specifically, private buses, buses and trams, and subways, with an assumed ratio of 2:34:143 [30], it is determined that at equivalent passenger volumes, bus and tram services can decrease the unit carbon emissions of private buses by 86%. In comparison, subway systems can achieve a reduction of 95% in carbon emissions per unit.

Additionally, if the highway traffic structure transitions towards public transport at an average annual rate of 5%(with 74% attributed to buses and trams and 26% to subway travel, based on historical public transport proportions), the adjusted unit emissions are predicted to decline from 2,049,100 kg CO_2/km to 219,400 kg CO_2/km. This transition would consequently reduce overall carbon emissions by approximately 4%, with the effectiveness of this carbon reduction strategy anticipated to enhance in correlation with the increasing share of clean electricity generation.

3.2. Intelligent Management of Road Circulation

Rising demand for passenger transport complicates road traffic management, posing challenges to carbon reduction goals. A vehicle's fuel consumption depends on its weight and operating conditions. Fuel consumption at lower speeds can be about 50% higher than at higher speeds, and congestion worsens emissions from low-speed driving. Smart transportation is becoming a practical reality with technological advancements and AI integration. Optimizing roadway networks with multiple lanes and varying speed limits can reduce carbon emissions from traffic jams. Additionally, AI-driven traffic allocation will consider energy consumption to alleviate road congestion [31]. The Cooperative Vehicle-Infrastructure System (CVIS), including active (A-CVIS) and passive (P-CVIS) components, enables the sharing of crucial traffic information [32]. These measures are expected to reduce low-speed travel time by 11%, leading to a 3% to 7% decrease in fuel consumption and carbon emissions. Shortly, urban transportation will evolve from static, manual data collection to dynamic, automated systems that improve the predictive accuracy of traffic flows and support energy-efficient roadway designs. This change is crucial for sustainable transportation networks.

Intelligent traffic interventions yield varying impacts based on vehicle powertrain type. Internal combustion engine vehicles (ICEVs) perform best in high-speed suburban areas, while BEVs excel in urban settings with heavy traffic, especially in stop-and-go conditions. This advantage comes from their regenerative braking, efficient powertrains, and auxiliary systems that reduce congestion. Additionally, data show that gasoline and diesel vehicles achieve average energy consumption reductions of about 13%, 25%, and 17%. Thus, road circulation management must consider the unique characteristics of emerging powertrain technologies [33].

3.3. 'Road-to-Rail' and 'Road-to-Water' in the Freight Field

Promoting public road traffic to rail or waterway transport is a viable energy conservation and emission reduction strategy, particularly in the freight sector with the highest emissions [34]. Rail transport is about 75% electrified, surpassing road transport's electrification rate. Notably, 8% of global passenger travel and 7% of cargo transport account for just 2% of the transportation sector's total energy consumption [35], significantly reducing overall emissions [36].

To balance carbon emissions, transportation efficiency, and employment, optimal freight turnover ratios for rail, road, water, air, and pipelines are 14.76:29.75:52.52:0.10:2.87, evolving by 2023

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to 14.82:30.06:52.83:0.12:2.17. From 2019 to 2023, carbon emissions dropped by about 12.7%, revealing regional development disparities [37]. High-speed rail networks reduced carbon emissions by an average of 2.3%, mainly benefiting northern cities and urban areas [38]. Strengthening high-speed rail capacity while reducing road transport can decrease energy consumption by 10% and cut carbon emissions from intercity transport by 6.9%. Commercial intercity transport may achieve a 31.4% reduction in carbon emissions [39].

With rising transportation demand and limited technology, effective transitional policies in technology, structure, and management are essential to achieving carbon reduction goals in road transport. Although technological progress may be slow in the next five years, enhancing public transport occupancy and replacing 5% of private transport with public options could lead to a 4% annual carbon reduction. Managing peak congestion may also cut carbon emissions by 5.2% to 6.8%. Shifting bulk goods transport to rail and maritime, alongside local adjustments, will support balanced regional development.

4. Electric Power Drive Technologies on the Emission Reduction Potential of Highways in Anticipation of New Energy

Adjusting the transportation structure can only address short-term emission reduction challenges while improving energy efficiency and substituting certain fuels, which also exhibit limitations. Since the energy efficiency of pure electric vehicles is reported to be three times greater than that of internal combustion engine vehicles [40] and an increase of 57.8%[41], pure electric vehicles represent a relatively advanced form of new energy technology from a sustainable development perspective.

Mid-sized electric vehicles (EVs) are employed to evaluate their life-cycle carbon reduction compared to traditional internal combustion engine vehicles (ICEVs) from top automotive brands over the past decade (as listed in Table 5). Within optimal initial EV range of 564.2 km, battery electric vehicles (BEVs) reduce operational carbon emissions by 58.2% compared to ICEVs, showcasing significant environmental advantages in the operational phase vehicles.

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

Type	Production stage		Use phase	Abandonment phase	
	Exclude production of power batteries (kg CO_2/vehicle)	Power battery production (kg CO_2/kWh)	Characteristic parameters	Secondary usage	Reclaim
ICEV	6500	/	The combined fuel consumption (gasoline) is 0.08015 L/km [30]	/	580 kg CO_2/vehicle
BEV	8900	110	Power consumption:13.4 kWh/100km NCM532: 450kg,168Wh/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_2/kWh [42]	Without power battery: 510 kg CO_2/vehicle; (Hydrometallurgical recovery) power battery: -69.7 kg CO_2/kWh [43]

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A strategy to promote road vehicle electrification, alongside a 2% annual increase in electricity's share of energy, can effectively address short-term transportation emission pressures and enable a 45.9% carbon reduction [39]. The connections between battery technology, manufacturing, power sources, and operations significantly affect carbon emissions, showing positive and negative traits. Therefore, a detailed analysis of electric vehicles is essential to evaluate their emission reduction potential and define their role in China's low-carbon highway transportation development.

4.1. Development Level of Battery Performance for Pure Electric Vehicles

BEV operation is fundamentally dependent on high-energy-density battery storage systems. While BEVs are recognized for their environmentally friendly attributes during operation, the ecological implications associated with the carbon footprint generated from energy-intensive manufacturing processes and the recycling of used batteries must be considered, as the penetration rate of BEVs in both the passenger and commercial vehicle sectors continues to escalate.

Figure 4 demonstrates the production of BEVs categorized by battery type [44]. Among the prevalent types of power batteries are lead-acid, nickel-metal hydride, nickel-chromium, and lithium-ion batteries (LIBs), which encompass variants such as lithium manganese oxide ($LiMn_2O_4$, LMO), lithium iron phosphate ($LiFePO_4$, LFP), and lithium nickel cobalt manganese oxide ($LiNi_xCo_yMn_zO_2$, NCM). Furthermore, sodium-ion batteries (SIBs) are under development, focusing on the production of ternary lithium batteries and lithium iron phosphate batteries, which are witnessing significant rapid growth.

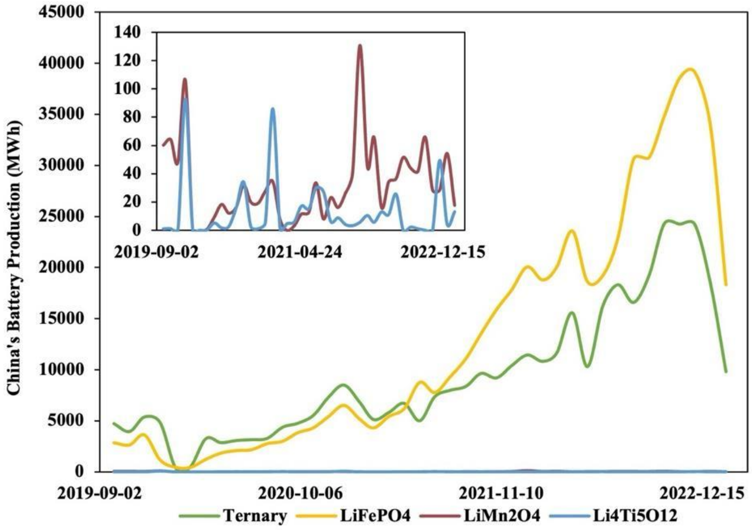

Figure 4. Production of various battery types utilized in pure electric vehicles [44].

The Life Cycle Assessment (LCA) and Input-Output (I-O) methods analyze life-cycle carbon emissions of various battery characteristics, as listed in Table 6. From 2008 to 2020, lithium batteries' mean energy density increased sevenfold. However, lithium-ion battery systems (LIBs) experience reduced energy and power density at lower temperatures and have high price volatility due to inconsistent raw material supply. Conversely, sodium-ion batteries (SIBs) offer a complementary technology with a stable supply chain and lower carbon emissions, making SIBs a promising battery technology in the future.

Table 6. Characteristics and functional units of power batteries with corresponding total carbon emissions.

Battery Kinds	Characters	Energy Density (Wh/kg) [45]	Function Unit	Carbon Emission (kg CO_2-eq)	Methods	Cycle Life

NCM111	High energy, high power, low cost, environmental protection, and long life [46], but the thermal stability is poor, with NCM and LFP series as the development mainstream.	160	1kg 1kWh 1kWh	21.81 136.31 130.4	LCA [47] LCA [47] CML CED [48]	
NCM532		170	1kg 1kWh	18.91 111.24	LCA [47] LCA [47]	
NCM622		180	1kg 1kWh 1kWh 1kWh	20.97 116.5 93.56 93.57	LCA [47] LCA [47] CML-IA [49] ReCiPe [49]	1000-2000
NCM811		200	1kg 1kWh	21.74 108.7	LCA [47] LCA [47]	
NMC811 NMC622 NMC523 NMC111		150-220	1kg	8.2-9.1	MiLCA [50]	
LiFePO4		140	1000kWh 200000km	736.35 8827	EPD2008 [51] CED CML-IA [52]	1000-2000
Li4Ti5O2		50-80	1kWh	400	LCA [53]	3000-7000
LiMn2O4		100-150	200000km	1866	CED CML-IA [52]	300-700
LICoO2		150-200	1km	149(g)	ReCiPe [54]	500-1000
Lead-acid	High safety, strong recyclability, low life span, and high maintenance cost [55]	20-35	1kWh	102.76(g)	ReCiPe [56]	250-1500
Ni-MH	Long service life, environmental protection but poor stability	60-80	1kWh	1.484	EPD2008 [51]	800-1200
Ni-Cd		40-60				
NaPBA	Low-temperature performance and safety characteristics, high recovery value but low energy density [55]	105.5	1kg 1kWh	13.72 130.05	LCA [47]	>3000
NaNMMT		146.1	1kg 1kWh	14.76 101.03		
NaMMO		133.5	1kg 1kWh	8.47 63.45		
NaMVP		129.6	1kg 1kWh	9.55 73.69		
NaNMC		115.9	1kg 1kWh	13.4 115.62		
NaS		116	1kg 1kWh	13.9 119.83		

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Furthermore, it is observed that advancements in battery technology are concomitant with reductions in the carbon emissions of functional units. Hence, energy density is a critical parameter for assessing battery performance. The innovation and development of battery technology necessitate the optimization of energy density to promote low-carbon environmental stewardship, thereby facilitating the iterative enhancement of electric vehicle capabilities, which involves striving for an equilibrium between reduced carbon emissions and elevated energy density.

4.2. Factors Influencing Carbon Emissions in Battery Manufacturing

The stage of battery production encompasses the extraction and utilization of various materials, which is often overlooked in discussions of environmental impact. As demonstrated in Figure 5, the discrepancies in emissions attributable to different battery material systems are primarily associated with components such as cathodes, cathode active materials, forged aluminum, electrolytes, and shells. Notably, the contribution of cathode materials to the carbon footprint, water footprint, and material footprint is significantly elevated, with its proportional impact increasing in correlation with the concentrations of nickel or cobalt in the battery, primarily due to the higher carbon emissions linked to the mining and refinement processes associated with these metals.

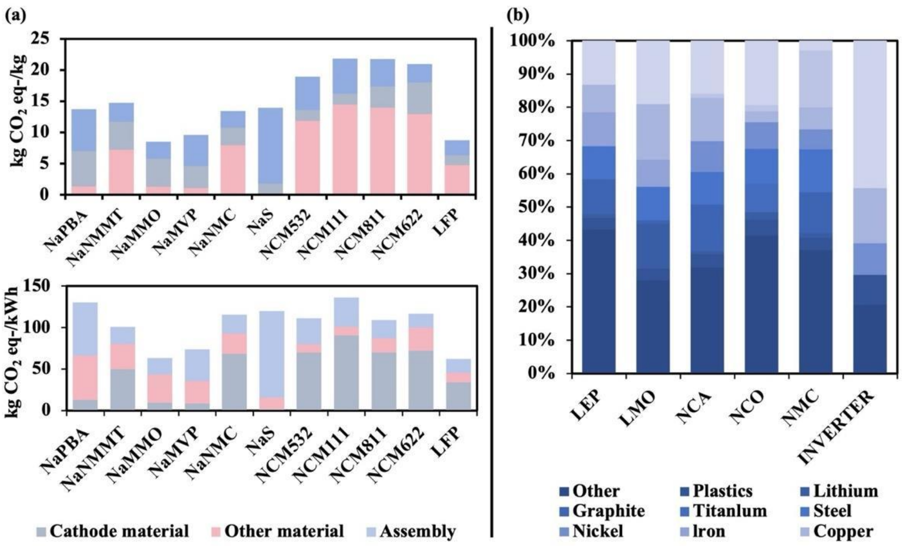

Figure 5. Carbon emissions of batteries: (a) associated with electrode materials [47] ; and (b) sharing ratio of various materials [53].

Conversely, most anode materials are graphite, characterized by mature technological applications and relatively low emissions. With advancements in lithium-rich low-carbon battery technologies, such as lithium-air batteries, the environmental impact during production may be reduced by 4-9 compared to traditional lithium-ion batteries [57].Furthermore, a relative reduction in emissions is associated with sodium-sulfur (NaS) batteries when utilizing electrical energy [47]. The advancement of lithium-rich, low-carbon technologies is becoming increasingly critical. It encompasses enhancing cathode active materials alongside developing complementary technologies such as sodium-ion batteries(SIBs). Consequently, raw material consumption and power efficiency are primary determinants of the production process's substantial environmental impact.

Battery manufacturing significantly contributes to the environmental ramifications of battery electric vehicles(BEVs), accounting for over 30% of total carbon emissions [58]. If these issues remain unaddressed, the environmental impact will be projected to escalate by more than 40% [59].

4.3. Indirect Effects of the Battery Charging Phase Derived from the Power System's Structure

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Figure 6 demonstrates the change curve of public charging infrastructure in China from 2016 to 2022. This infrastructure exhibits varying developmental conditions across different cities, with a predominant concentration in first -tier urban areas, and will parabolically grow in the following decade. Given that a 1.21% increase in charging power correlates with an 8.01% increase in grid power consumption [47], the accelerated adoption of electric vehicles is anticipated to impose substantial stress on the electrical grid. Since the power grid in China is predominantly supported by thermal power generation plants, the indirect carbon emissions generated during the operational phase are more severe than those from the battery production process.

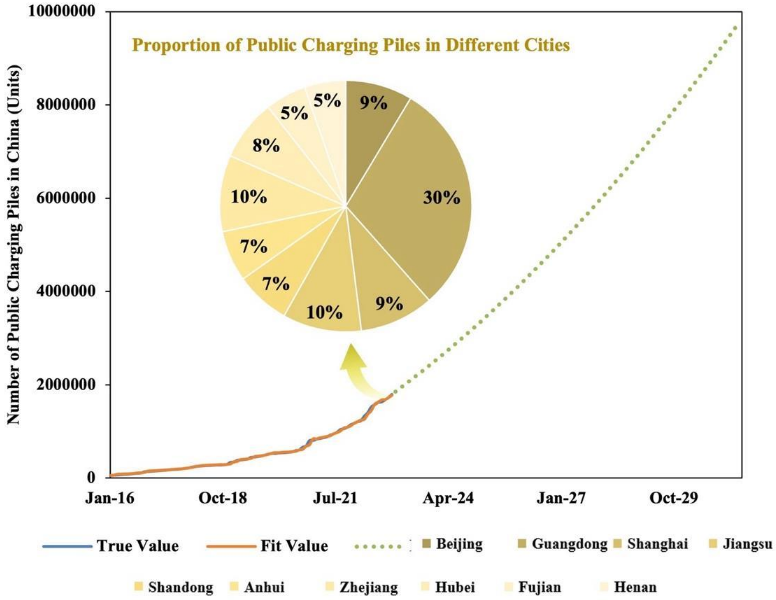

Figure 6. Predicted fitting curve for the monthly number of public charging stations in China from 2016 to 2030 utilizing time series methodologies.

The shift from hydroelectric power to coal (domestic and distributed systems) has led to a notable increase in total carbon emissions, which has subsequently heightened the impact of carbon emissions during the utilization stage, particularly affecting a wider variety of battery life cycles. Currently, coal constitutes approximately 70% of China's power generation mix. Lithium manganese oxide (LMO) and lithium iron phosphate (LFP) batteries from China, reliant on coal power, show carbon emissions 2.8% and 14.4% higher than those made in Europe, indicating varying battery performance development [52].

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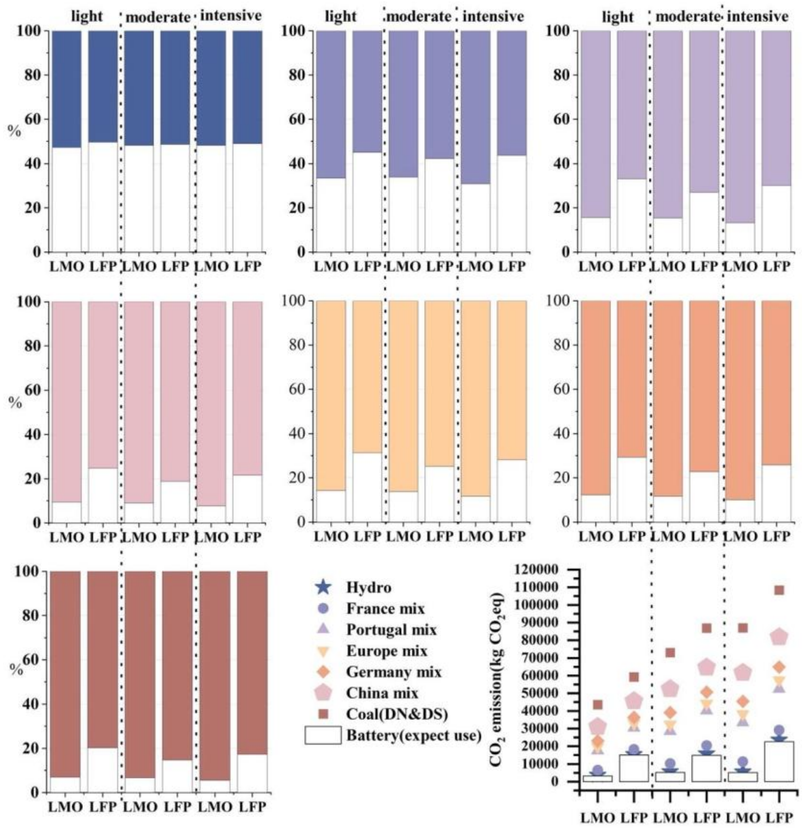

Figure 7. Carbon emissions of LMO and LFP batteries under different power generation combinations [52].

The power structure of China is undergoing a deliberate transition towards low-carbon alternatives, which suggests potential reduction in carbon emissions associated with the operation of the specified batteries, like the environmental impact related to the battery during the life cycle would decline by 7.9% or 8.2% if 10% of China's coal-fired power generation can be supplanted by wind or hydropower [60]. Meanwhile, charging stations with 20% penetration of solar PV will reduce carbon emissions by 5411.18 kgCO_2/day per day and reduce carbon emissions from vehicles to the grid by 10.08t CO_2 [61].

In light of China's projected substitution rates of 25% and 100% for coal-fired power generation by the years 2030 and 2060 [62], respectively, it can be anticipated that the greenhouse gas emissions associated with battery production will decrease by approximately 30% and 90% relative to the levels recorded in 2020, as demonstrated in Figure 8 [63]. When the share of renewable energy exceeds 60%, carbon emissions produced during the battery production and end-of-life phases are also diminished; however, these emissions remain significantly higher than those associated with the battery operation phase. Microgrid systems are more suitable for utilizing undulated renewable energy sources (like wind and/or solar energy), whose costs on operation and environmental issues significantly influence the carbon emissions of BEVs via the impacts on charging management [64].

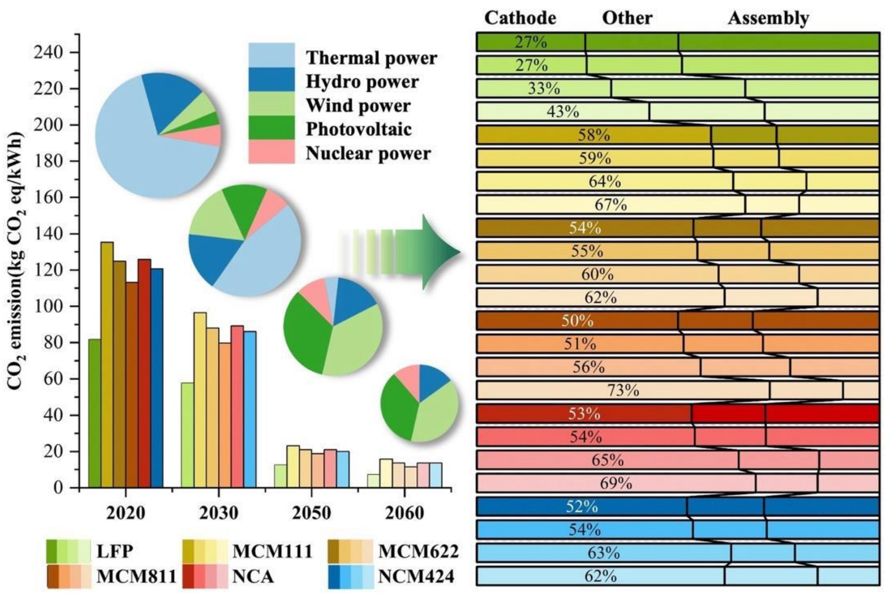

Figure 8. Prediction of carbon emissions associated with different strategies of China's power generation in the future [63].

From the standpoint of national policy frameworks, adjusting domestic power generation structures significantly reduces the environmental impacts of battery utilization. Meanwhile, transitioning from traditional power grid structures to microgrids necessitates adopting decentralized power supply systems. This shift is imperative for enhancing the power grid's flexibility, efficiency, and stability, supporting electric vehicle deployment and advancing energy conservation and emission reduction objectives.

In developing policies to enhance electric vehicle adoption rates, local governments must rigorously assess many factors, encompassing energy storage systems, electric vehicle range, peak load demand management, and the extent of public charging infrastructure. Moreover, it is essential to thoroughly evaluate charging schedules and rates to respond to the escalating demand for electricity adequately. This comprehensive approach will facilitate flexible and dynamic adjustments to varying energy requirement conditions. 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 the overall economy [65].

4.4. Carbon Emissions During Battery Operation

In the context of energy conversion technologies, the efficiency of energy conversion and the energy demands associated with the mass of the battery significantly influence the carbon emissions during BEV operation. It is important to note that the impact of conversion efficiency is estimated to be between 2 and 6 times greater than that of battery weight, assuming an internal efficiency of 90% [66]. Based upon the data listed in Table 5, various battery form factors(including pouch, cylindrical, and prismatic), as well as different cathode materials, yield distinct round-trip efficiencies, which refer to the amount of electricity dissipated by the battery throughout each complete charge-discharge cycle. These variables inherently affect the energy conversion efficiency of the overall system, thereby influencing the associated carbon emissions of the functional vehicle units.

The characteristics of batteries encompass various factors, including chemical composition, internal efficiency, weight, and power, as well as design parameters such as electrode configuration, porosity, and charge-discharge cycle performance. Empirical studies indicate that lithium-ion batteries exhibiting around-trip efficiency of 90% demonstrate the least environmental impact during their operational phase. In contrast, vanadium redox flow batteries, characterized by around-trip efficiency of 75%, present a significantly more significant impact during usage. Additionally, low

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energy density necessitates deploying a more substantial number of batteries under equivalent operational conditions, resulting in an increased system mass that adversely affects carbon emissions. As demonstrated in Figure 9, the environmental impact of NCO-LTO batteries is approximately double that of alternative battery types. Consequently, enhancing energy density emerges as a critical avenue for reducing carbon emissions associated with battery technology [53].

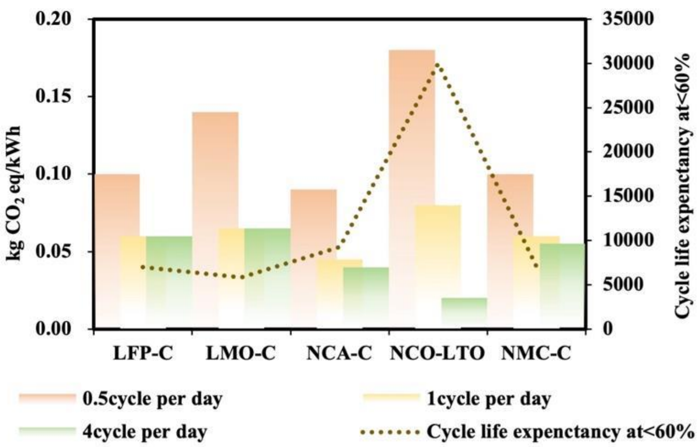

Figure 9. Comparison of carbon emissions of various batteries under different cycles [53].

Energy density is intricately linked to battery materials; however, these materials and their corresponding chemical reactions also limit cycle life. Based on the reported data [67], the cycle life of NCO-LTO batteries significantly surpasses that of other types, as demonstrated in Figure 10. Research examining 0.5, 1, and 4 cycles per day for the battery above types reveals that NCO-LTO achieves over 50% lower carbon emissions during frequent usage due to its life cycle advantage. Therefore, optimizing battery materials and designs to enhance the cycle life of high-energy density batteries is imperative, thus broadening their operational range benefits.

The reported data [67] shows that alterations in operating temperature from the reference value of 25°C to 15°C or 45°C correspondingly reduce the number of battery cycles from 2810 to 2420 to 930 cycles, respectively. The findings mean operating temperature during cycling is a critical parameter significantly affecting the SoC and discharge characteristics since it is vital in mitigating battery aging and reducing the rate of decline in round-trip efficiency through effective thermal management. Furthermore, within defined temperature parameters, the optimal range for cycles is identified as 50% for the average SoC and 30% for the DoD in a centralized manner. Thus, effective thermal management can enhance cyclic performance and reduce carbon emissions through appropriate operating temperatures and design parameters.

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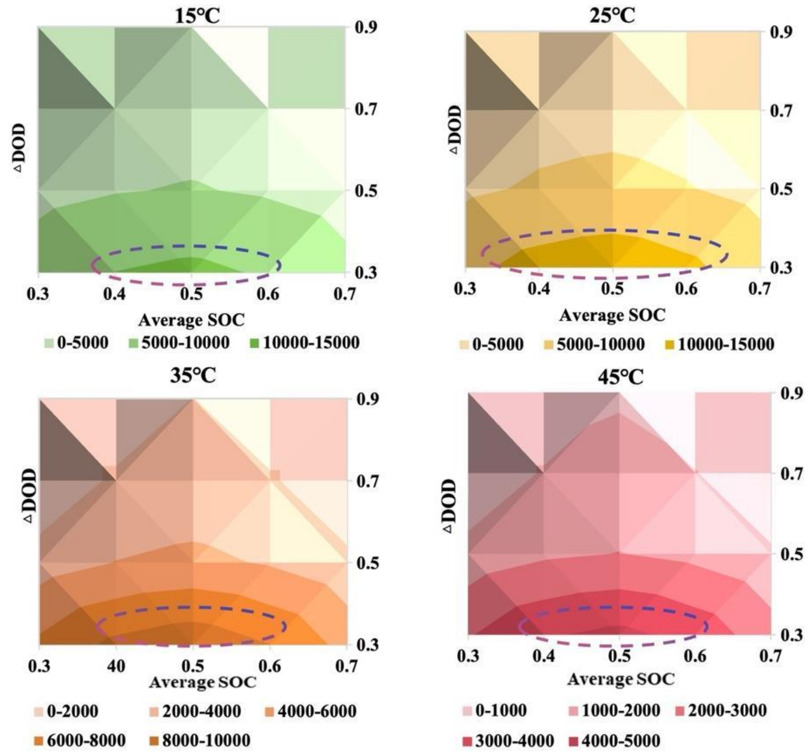

Figure 10. Comparison of the degradation rates of Lithium-ion battery cathodes under different cycling frequencies [67].

However, frequent charge and discharge cycles can adversely affect the capacity retention rate, substantially increasing carbon emissions per functional unit [53], which means that the user's charging cycle and management strategies are also crucial determinants of battery performance. Figure 11 demonstrates the correlations of carbon emissions to battery performances, including round-trip efficiency, cycle frequency, power consumption, and energy-specific power, based on the reported data [69]. From the correlations, it can be regarded that carbon emissions are less dependent on the average power output, with a 3% reduction by a 5% increase in power; however, carbon emissions are highly sensitive to the battery's round-trip efficiency, with 3% reduction by a 1% enhancement in round-trip efficiency.

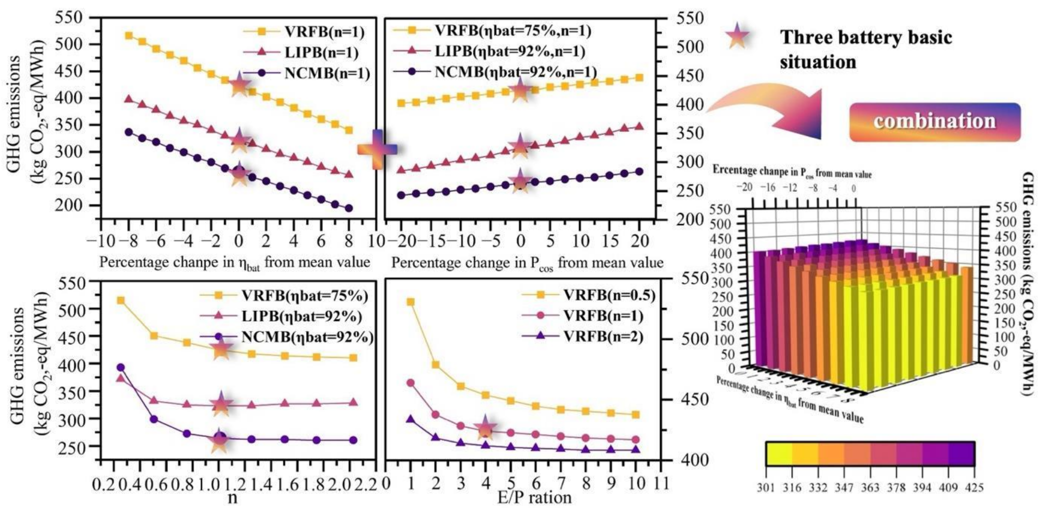

Figure 11. Correlations of carbon emissions to the battery performances, including round-trip efficiency, cycle frequency, power consumption, energy, and power ratio [69].

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From various aspects of the analysis mentioned above, pure electric vehicles are believed to assume a progressively crucial role within the urban transportation and private vehicle markets, and enhancing the penetration rate of electric vehicles is recognized as an essential and viable strategy for facilitating the low-carbon development of the highway transportation sector in China within the short to medium term. However, with the current technologies, BEVs possessing range exceeding 700 kilometers demonstrate negligible carbon reduction effects [70]; consequently, the primary focus for advancement resides in the innovation of battery performance to mitigate constraints related to carrying capacity range. In addition to performance impacts, the indirect carbon dioxide emissions during the operational stage and the emergence of new pressures must be considered. The power sector faces a transition towards heightened production pressures and challenges associated with carbon emissions. Consequently, there is a critical need to enhance the power structure and ensure the stability of the power grid to facilitate the advancement of zero-carbon vehicles.

5. Potential for Carbon Reduction Through Hydrogen Fuel Cell Technology Vehicles

5.1. Potential of Carbon Reduction by Hydrogen Fuel Cell Vehicles

Hydrogen, as a high-energy-density and zero-carbon energy source, offers several advantages, including high energy efficiency, diverse sourcing capabilities, and pollution-free emissions, and has been widely regarded as one promising alternative fuel in the future. HFCVs are driven by the electrical power generated onboard by the electrochemical reaction of hydrogen and air (as demonstrated in Figure 12) rather than downloaded from the grid, meaning they can solve the carbon emissions from the electricity generation. Meanwhile, fuel cells do not adhere to the efficiency limits of the Carnot cycle, thereby enabling improved efficiency and significantly enhancing the mileage of vehicles [71].

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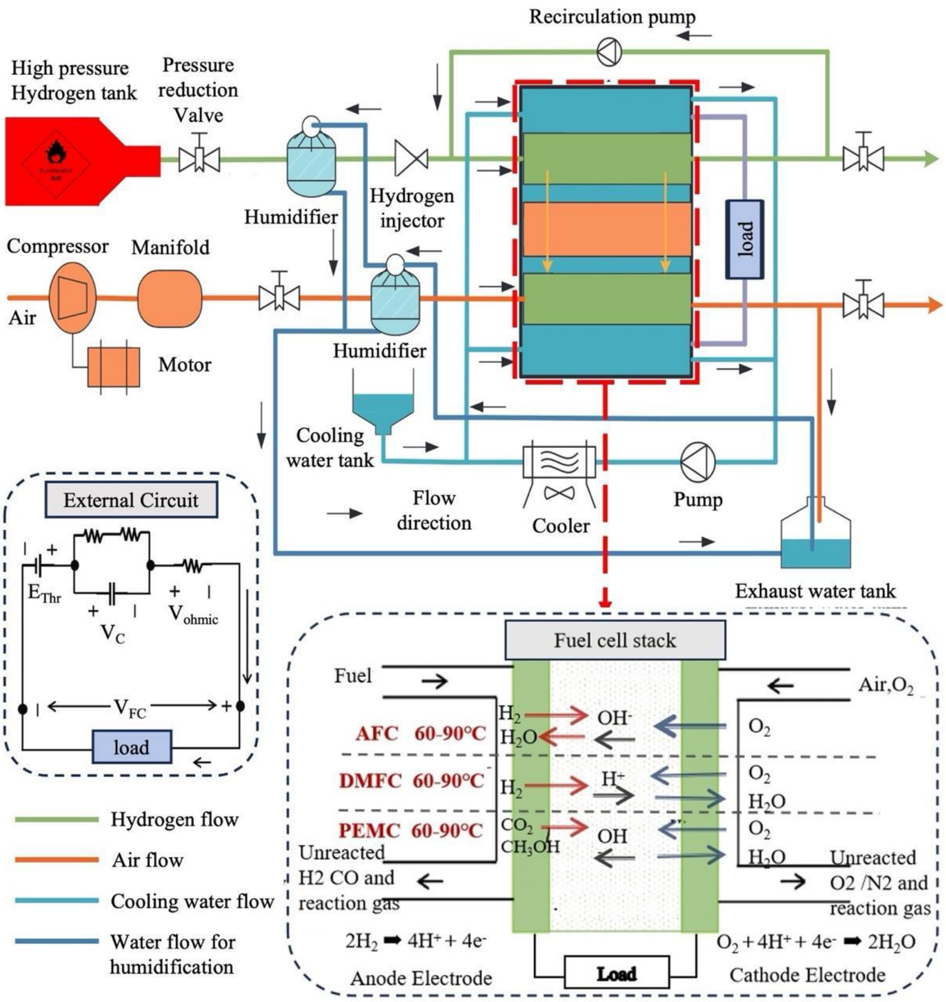

Figure 12. Principle of operation of hydrogen fuel cells.

Compared to ICEVs, HFCVs can reduce energy consumption by approximately 29% to 66%, together with a reduction in greenhouse gas emissions of 31% to 80% [72].Notably, the larger the specifications of hydrogen refueling vehicles in the short term, the more pronounced the carboreduction effect will be, 3.72% higher than that observed in vehicles utilizing electric substitution [72]. Consequently, hydrogen refueling has progressively emerged as a viable alternative for heavy-duty vehicles, such as buses [74], and large and medium-sized commercial vehicles. By 2030, it is anticipated that these vehicles will achieve a whole life cycle economy comparable to pure electric vehicles, thereby accelerating penetration within heavy-duty truck models and facilitating significant expansion throughout the entire transportation sector by 2050 as technology advances and the cost of hydrogen decreases.

In China, the New Energy Vehicle Industry Development Plan (2021-2035) incorporates the establishment of a stable hydrogen fuel cell supply into its overarching vision, while the Outline of the National Innovation-Driven Development Strategy for 2020 has set a target of exceeding 2 million hydrogen fuel cell vehicles by the year 2030. Despite these ambitious projections, sales of hydrogen fuel cell vehicles have demonstrated a relatively subdued performance over the past five years, exhibiting a fluctuating downward trend with a growth rate significantly lower than that of pure electric and plug-in hybrid vehicles, indicating that hydrogen fuel cell technology is currently in a quasi-large-scale commercialization phase. In response to these challenges, the Chinese government has implemented a series of policies to foster the development of the hydrogen fuel cell industry. These policies emphasize the importance of technical innovation and practical application, targeting key technologies related to efficient hydrogen production, storage, and transportation alongside advancements in refueling infrastructure and fuel cell technology. Nevertheless, the collaborative efforts of all stakeholders necessitate a scientific investigation into whether the development of hydrogen energy in conjunction with renewable energy can attain synergistic efficiency. This inquiry warrants comprehensive analysis and in-depth exploration discussion.

5.2. Indirect Effects of Hydrogen Production

As listed in Table 7, hydrogen can be produced by various technologies from abundant feedstock with remarkable advantages. However, most hydrogen production methods depend on the feedstock containing carbon, which suggests the contribution of carbon emissions from hydrogen fuel cell vehicles is predominantly influenced by the specific production route employed in hydrogen generation. Approximately 99% of hydrogen production in China is sourced from or associated with fossil fuels, which release substantial carbon emissions [17]. To address the mentioned conflict between hydrogen production and carbon emissions, central and local governments in China have implemented comprehensive policies to promote green hydrogen development in recent years.

Table 7. 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 H2 yield (90.9%), low CO selectivity (0.61% at 280°C), optimal Cu/Zn ratio [74].
Dark Fermentation (DF), Co-precipitation, Hydrothermal, Sol-gel	Organic renewable carbon sources	✧ Biomass-based hydrogen production by dark fermentation	✧ High biohydrogen yield, improved bioconversion, and enhanced energy recovery through advanced pretreatments and designs [75]
Electrolysis using aqueous polyoxometalate (POM)	Native biomasses	✧ High efficiency hydrogen evolution from native biomass electrolysis	✧ No noble-metal catalyst, low energy use, and can use sunlight/heat for reactions, no chemical pretreatment needed [76].
Photo Fermentation, Pre-treatment (banana peels)	Brewery wastewater	✧ Improvement of 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 [77].
Solar-driven steam-autothermal reforming (EISAR)	Solar energy, Natural gas	✧ Solar energy driven steam and autothermal combined reforming system for hydrogen production	✧ Produces hydrogen, urea, electricity, and heat, powering 400 households with zero carbon emissions [78]
Thermodynamic analysis and life cycle assessment	Coal	✧ Utilizing supercritical water technology for co-producing hydrogen from coal-fired power plants	✧ Higher energy and exergy efficiency, lower emissions compared to IGCC, combined with Organic Rankine Cycle (ORC) [70].

Green hydrogen is produced through water electrolysis utilizing renewable energy sources, including wind, solar, and geothermal energy. This production process is characterized by its minimal carbon emissions, contributing significantly to reducing the carbon footprint and fostering the efficient utilization and consumption of renewable e nergy. However, the high costs associated with the production of green hydrogen have hindered its adoption as a mainstream solution in large-scale applications. Therefore, advancements in hydrogen production technology are essential for the widespread implementation of hydrogen refueling infrastructure. Additionally, a well-considered growth strategy for electric and hydrogen fuel vehicles is imperative to ensure an orderly balance between carbon emissions at both the production and utilization stages.

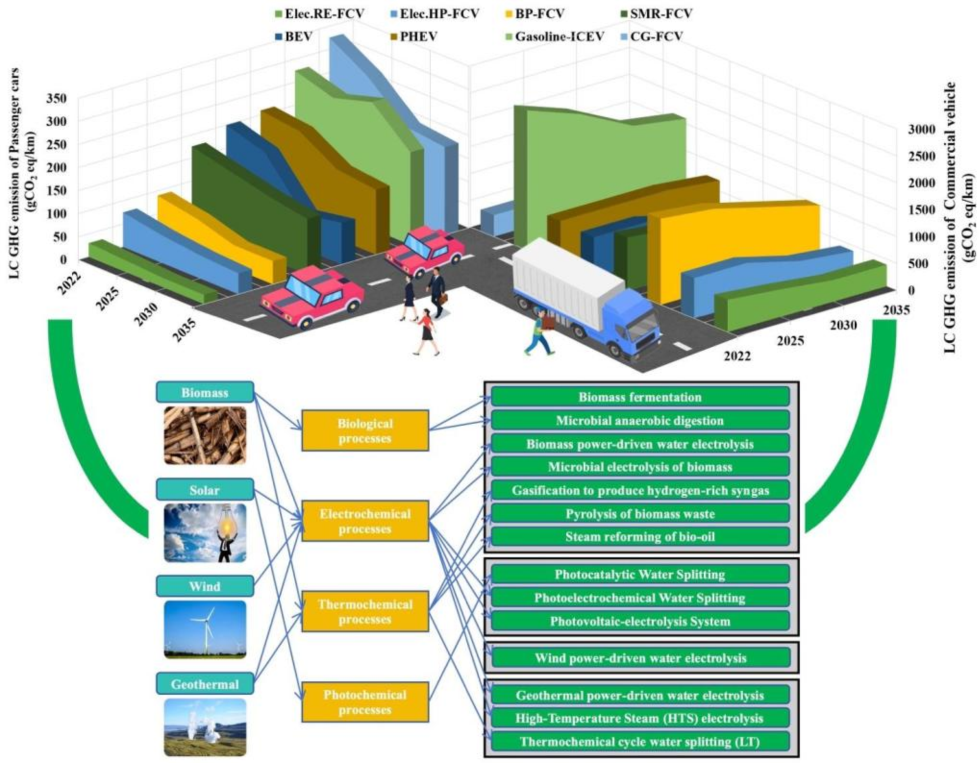

Figure 13. Prediction of carbon emissions of electric vehicles by different hydrogen production sources [81–83].

Figure 13 demonstrates the lifecycle carbon emissions of fuel cell vehicles, encompassing both passenger and commercial vehicles, under the projections for renewable energy development for 2025, 2030, and 2035, upon the data predicated by GRA- BiLSTM model [80] and the available paths of green hydrogen production [81–83]. Among these vehicle types, the carbon emissions associated with coal gasification (CG) as the primary hydrogen production method in China are the most substantial, followed in severity by steam methane reforming (SMR), biomass pyrolysis (BP), electrolytic hydrogen production using hydroelectric power (Elec.HP), and electrolytic hydrogen production from renewable energy (Elec.RE). It is anticipated that with enhancements in fuel economy and advancements in battery and hydrogen production technologies, the lifecycle carbon emissions per fuel type will experience a reduction of approximately 5-10% by 2035, relative to those recorded in 2022. Nevertheless, it is essential to note that the lifecycle carbon emissions associated with various fuel types in commercial vehicles exceed those of passenger vehicles. An IEA [84] analysis posits that the cost of hydrogen produced from renewable electricity, termed "green hydrogen," may decline by 30% by the year 2050. As the price of renewable energy continues to decrease, particularly with the ongoing advancements in solar and wind energy technologies, the market share of green hydrogen is anticipated to expand progressively.

5.3. Market Potential and Current Challenges of Hydrogen Fuel Cell Vehicles

Under optimistic projections, global investments in hydrogen energy within the transportation sector are anticipated to attain a value of 64 billion yuan by the year 2030 [85]. To China, hydrogen fuel is projected to fulfill 28% of the energy demand for transportation by 2050 [86], and the reduction of carbon emissions is expected to achieve a substantial decrease of 340 million tons annually by 2060 [87]. To realize the objectives outlined in the 'Dual Carbon' goals, projections indicate that the anticipated number of fuel cell vehicles in China by the year 2034 will reach 549500, 2351700,and 8844100 by the year 2035, according to the predicted scenarios of low growth, baseline, and high growth respectively[80]. However, a substantial discrepancy exists between current ownership levels and established targets in the contemporary Chinese automobile market. Furthermore, the existing supply potential proves insufficient to meet these objectives and goals.

The low penetration rate of hydrogen refueling stations (HRS) constitutes a significant barrier to the advancement of hydrogen fuel cell electric vehicles (HFCVs) within the Chinese automotive sector. Implementing HRS requires a thorough assessment of safety protocols, encompassing the distribution of hydrogen and the detection of potential leaks[88]. Furthermore, it requires careful consideration of construction variables such as supply chain location, prevalent local travel patterns, and prospective acceptance by the public. An optimal balance must be achieved between storage and transportation costs while addressing safety concerns. This entails employing diverse supply routes and storage solutions tailored to various business formats and the characteristics of gaseous hydrogen, encompassing both off-site and site configurations and gaseous and liquid states.

Concurrently, this approach can mitigate conversion stages and significantly enhance system efficiency [89]. For instance, the implementation of integrated hydrogen refueling stations, direct current (DC) interconnection solutions [90], or multi-module hydrogen stations [89] is advisable. Adopting a judiciously formulated strategy for HRS can elevate electric vehicle sales by a minimum of 40% and augment market diffusion efficiency by 76.7% [91]. The breakthroughs in hydrogen production technology, coupled with advancements in hydrogen storage and transportation technologies, alongside the establishment of a comprehensive hydrogen refueling station network [92], will be pivotal for the scale implementation of hydrogen energy.

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

The quantitative findings support a vision for the transition to low-carbon transport from 2025 to 2050, as demonstrated in Figure 14, after analyzing the evolution of China's low-carbon road transport policy, carbon technologies, and their carbon reduction impacts. The roadmap categorizes the development trajectory into three stages: short-term pressure transition, medium-term technological adaptation, and long-term sustainable development. It also proposes specific green development goals and strategies for China's road transport sector at each stage. These phases are described as a dynamic progression reflecting technological maturity and each stage's challenges.

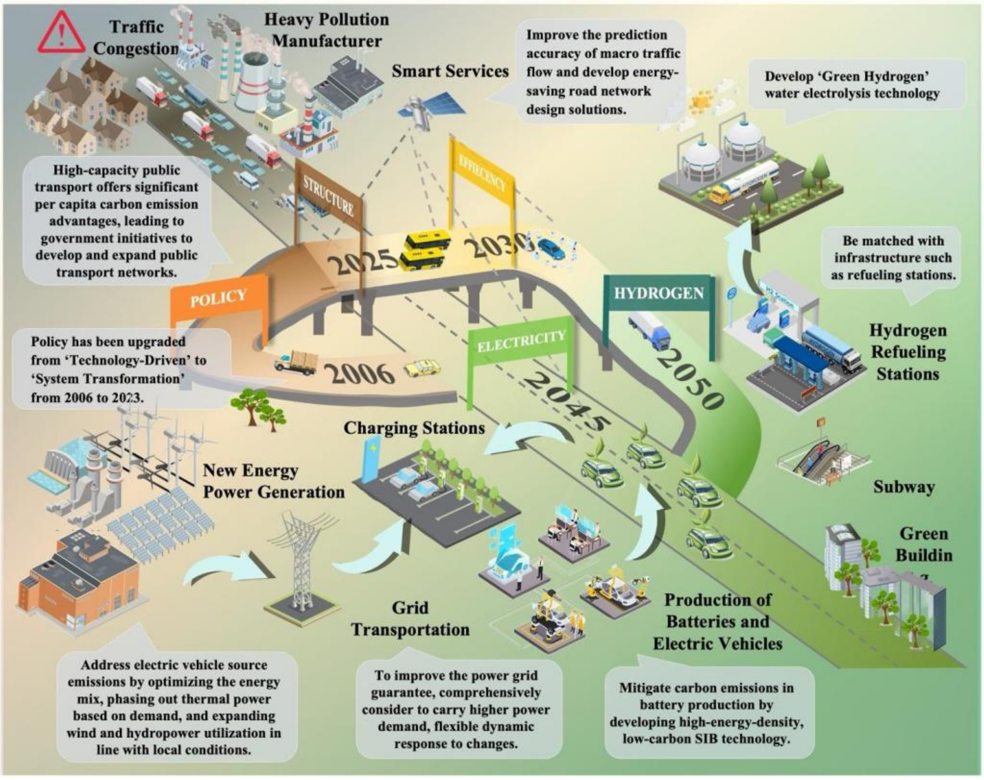

Figure 14. Analytical framework for the low-carbon transformation of China's road transport sector.

1. In the short term, from 2025 to 2030

Carbon reduction targets in road transport stem from rising demands for reductions despite slow technological advancements. Achieving these targets requires adjusting the transportation structure, which is low in technical complexity. This transition is essential for aligning with China's rapid economic growth while minimizing technological costs, thus helping the road transport industry move towards low-carbon, sustainable development.

Public transport decreases carbon emissions, including metro systems, light rail, high-speed rail, and electric buses. Governments are building infrastructure for a comprehensive network that boosts energy access, efficiency, and public transport use and integrates urban planning with a 'smart city' approach. A shift to public transport, expected to grow by5%, could lower emissions by about 4%. Enhanced carbon reduction depends on increased clean electricity generation. Improving bulk cargo methods like "road to rail" and "road to water,' enhancing railway infrastructure, and promoting multimodal transport are essential, with focused actions necessary to address regional disparities.

Carbon reduction in road transport often emphasizes individual vehicle emissions, neglecting the cumulative effect of congestion from increased vehicle ownership that degrades operating conditions. AI and 5G can enhance road management by creating smart systems during peak times to alleviate congestion, improve traffic flow predictions, and foster energy-efficient network designs. These measures are essential for sustainable transport and could cut carbon emissions by 3-7% through public infrastructure changes.

2. In the medium term, from 2030 to 2045

It requires transitioning from traditional energy sources to new power options, ensuring a systematic phasing out of conventional fuel vehicles. Since Battery electric vehicles (BEVs) have 58.2% lower carbon emissions than internal combustion engine vehicles (ICEVs) over the same mileage, scaling up end-use energy and low-emission electrifications is recognized as a crucial technology adaptation goal aligned with environmental, social, and economic values. Transitioning requires complex dynamics in upstream and downstream industries, highlighting the need for lifecycle carbon emissions assessment and inter-departmental coordination. Manufacturers must address emissions from battery raw materials, especially cathodes. Furthermore, enhancing research on

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cathode materials and exploring sodium-ion battery (SIB) technologies with higher energy density and lower carbon emissions is essential. By 2035, renewable energy's generation share may exceed 50%, with energy density improving by 1.5 times, potentially over 80% by 2045, cutting carbon emissions from battery use and production by over 70%. This could triple energy density, aiding the shift from fuel vehicles. Grid security will also improve, accommodating higher power demands and adapting to energy fluctuations.

3. In the long term, from 2045

Due to escalating demands for transportation, electric vehicles' battery performance and charging times are inadequate for medium- and long-distance travel, especially for heavy-duty vehicles. By 2050, hydrogen refueling vehicles will emerge as a viable low-carbon alternative. Hydrogen is mainly used in medium and heavy-duty fuel cell trucks and buses to enhance public transportation by increasing medium and heavy-duty vehicles. The strategy anticipates expanding to smaller vehicles, with projections by 2050 indicating heavy truck penetration will exceed 70% and small passenger cars will surpass 15%. The source of hydrogen production significantly affects its carbon reduction potential. The shift from "gray hydrogen," which has high carbon emissions, to "green hydrogen," produced through water electrolysis, is expected to lead the future market. By 2035 and 2045, renewable energy is projected to make up over 50% and 80% of the energy mix, fostering green hydrogen technology growth. Additionally, hydrogen vehicles require infrastructure like refueling stations, and regulating carbon emissions from gray hydrogen production is essential.

7. Conclusions

Since 2006, China has implemented low-carbon policies in road transport to meet emission reduction commitments. Government initiatives catalyze technological innovation and promote low-carbon development. This study examines central and local governance policies, assesses transportation technologies for market and technological maturity, and proposes a pathway for low-carbon transformation. The main conclusions are summarized as follows,

1. Economic and social development (11th Five-Year Plan 2006-2010 and 13th Five-Year Plan 2016-2020) and external factors (China's 'Dual Carbon' commitment at the UN in 2020) shifted policies from technology promotion to system transformation. Policies should align with regional characteristics, balancing central directives with local measures for megacities and smaller cities.
2. Public transport is a crucial answer to the growing demand for transportation noted in recent years, where per unit carbon emissions are over 50 times higher than private cars. The intelligent optimization of road traffic, combined with artificial intelligence technology, can significantly reduce pollution caused by city traffic congestion. Moreover, while freight transportation in China has struck a balance among economic, social, and environmental gains, regional development disparities require additional refinements.
3. Battery electric vehicles (BEVs) and their charging infrastructures are expected to grow significantly over the next decade. Sustainable raw material production is crucial for the electric vehicle sector to meet demands for better battery performance and lower carbon emissions throughout their life cycle. However, due to low carbonization in manufacturing, pressure to reduce emissions must shift towards clean transformations in power generation and improving power grid stability during operation.
4. Hydrogenation vehicles can overcome the range and charging limits of electric vehicles. However, the current grey hydrogen technology fails to fully utilize its carbon reduction benefits. Ongoing technical challenges in hydrogen production, transportation, storage, and hydrogenation highlight the need for significant advancements before large-scale market adoption can occur.
5. A road map proposes to outline "system transformation" in three stages. "Technology promotion" alone fails to meet short-term transportation demands; thus, a strategic framework for public intervention is crucial for transitioning to a low-carbon system. Optimizing power structures and technological advancements will likely lead to the successful adoption of pure

electric vehicles by 2030-2045. Additionally, hydrogen fuel vehicles will enter the market with hydrogen technology maturation, starting with heavy-duty applications and expanding to medium and light-duty vehicles after 2045.

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