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Current Implementation and Development Countermeasures of Green Energy in China's Highway Transportation

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Abstract: The transportation industry is one of the largest consumers of fossil fuels and sources of carbon dioxide emission, with highway transportation accounting for more than 70% of the total. In order to promote efficient, clean, diversified, and intelligent use of energy, this study proposes an innovative application technology model for integrating highway transportation and energy to improve the utilization of clean energy and reduce the proportion of fossil energy and carbon emissions in highway transportation. This study addresses the current problems of green energy development in China's highways, and combines green low-carbon development policies in international transportation with inspirations based on experience. Based on the principles of safety, efficiency, environmental friendliness, wisdom, and economy, this study systematically analyzes the current situation of green energy application in China's highway transportation. It proposes one core objective, two major roles, and five major security systems of development measures for green energy application China's highway transportation with the aim of promoting the transformation and upgrade of China's highway transportation industry. This study can also help to achieve green and low-carbon development of highway transportation and provides a decision-making reference for the ecological civilization construction goals of the industry.

Keywords: green energy application; development countermeasures; highway

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1. Introduction

With the rapid growth of highway transport demand, the scale of China's highway transport infrastructure construction continues to operate at a high level. Both the total energy consumption of the transport industry and its share of society's total energy consumption are increasing year by year. China's highway growth rate and operation size are among the fastest and largest in the world, and have become a vital support for national economic development and social welfare. However, despite the nation's need for a robust transportation system and high-quality development of highway transportation, highway transportation in China is still plagued by high emissions and substantial reliance on external energy sources. For example, domestic highway emissions account for 80% of the total emissions of the transportation system, and China's highway traffic carbon emissions account for a quarter of the world's total highway traffic emissions. It has become the third largest energy consumer after industrial and residential energy use [1]. Building a "safe, efficient, green, intelligent, and economical" transportation and energy integration and innovative application technology model, as well as promoting the deep integration of transportation and energy development, are therefore essential tasks for building China's strength in transportation in the new era.

Today's world is experiencing a century of unprecedented changes, the worldwide energy landscape has undergone significant transformations, and international rivalry is intensifying around the energy science and technology revolution and industrial transformation. Energy security is a global and strategic concern for China's economic and social development. As the energy crisis and climate change become major international concerns, "efficient, clean, diverse, and intelligent" energy consumption has become the fundamental concept and development objective of the energy strategies of major nations. In recent years, major developed countries have regarded green and low-carbon energy technologies as a breakthrough in a new scientific and technological revolution and industrial transformation. These countries have actively implemented and adjusted medium- and long-term energy science and technology strategies and used them as top-level guidance. They have also introduced major science and technology programs to mobilize continuous investment in social resources. They have continuously optimized and reformed their energy science and technology innovation systems to enhance national competitiveness and maintain their leading position [2,3].

In particular, Germany has consistently pushed for a change in energy structure that is renewable energy led. As a result of years of policy incentives and R&D support, Germany is now at the top of the world in renewable energy technology and equipment manufacturing. On July 27, 2022, the German Parliament approved the government's special "Climate and Transition Fund" program, which would invest EUR 177.5 billion over the next four years to expedite the transition to a cleaner economy and make the energy supply less reliant on Russia. The Swedish government introduced a series of bills to accelerate the policy goal of transforming transportation energy use. The content of these bills includes publishing a law that requires all large gas stations to provide at least one kind of renewable fuel, and proposing tax exemptions for vehicles with low or zero CO_2 emissions to reduce emissions of carbon, sulfur, nitrogen oxides, etc. This encourages energy-efficient technologies and the development of public transportation, as well as promoting decarbonization in the transportation sector [4]. Therefore, European countries, mainly Germany and Sweden, are actively developing highway electrification technologies with respect to transportation and energy. The United States has made significant progress in achieving transportation energy independence and realizing green energy transition by formulating the Comprehensive Energy Strategy [5] and supporting action plans, establishing innovation platforms such as the Advanced Energy Research Program and the Energy Innovation Center. These support transformative energy technology development, effectively integrating resources from all parties in industry, academia, and research, and promoting green energy technology revolution and industrial upgrade and transformation [6]. For example, the U.S. plans to achieve photovoltaic pavement and energy recovery through energy storage and smart microgrid construction. The European Union published The European Green Deal at the end of 2019, proposing the goal of carbon neutrality by 2050, in the context of which transportation carbon emissions will be reduced by 90%. The EU will develop stricter CO_2 emission regulations standards for vehicles to achieve this goal [7]. In 2016, Japan announced the Energy and Environment Technology Innovation Strategy in the government's Comprehensive Science, Technology and Innovation Conference, which identifies five major technology innovation areas that Japan will focus on until 2050, including building an intelligent energy integration management system using big data analysis, artificial intelligence, advanced sensing and Internet of Things technologies, developing innovative manufacturing processes and advanced materials for energy savings, implementing next-generation battery and hydrogen production, storage and application technologies, integrating the next-generation of photovoltaic and geothermal power generation technologies, and utilizing carbon dioxide by carbon capture [8]. The UK, Japan, and the EU are promoting progress in the electrification of public and shared transportation. Areas in China with completed power transmission systems, such as Xi'an, Shenzhen, and Guangzhou, are gradually achieving full electrification of urban public transportation and actively integrating the operation and maintenance of public transportation with the energy supply. China has also comprehensively assessed the potential of renewable energy and its methods of utilization for highway transportation infrastructure and developed a general technical standard for solar highway pavements and technical specifications for highway microgrid systems [9].

China is a country with limited oil reserves. The Domestic and Foreign Oil and Gas Industry Development Report released by the China National Petroleum Group Economic and Technical Research Institute shows that its oil dependency is 72.2%, and multi-purpose oil accounted for about half of the overall oil consumption in 2021. The rapid growth of transportation energy use has placed enormous pressure on China's energy security and presents a significant challenge with regard to climate change, regional environmental pollution, and sustainable development. China has proposed reaching a carbon peak in 2030 and achieving carbon neutrality in 2060. The effective use of green energy and the natural endowment of energy from transportation assets has become an urgent need for science and technology innovation to support the transportation energy structure [10]. The Outline of the Construction of a Strong Transportation Country [11] and the Outline of the National Three-Dimensional Comprehensive Transportation Network Planning [12], published by the State Council of the Party Central Committee, propose to "optimize the transportation energy structure" to vigorously promote "new energy and green energy applications" and achieve the "early peaking of carbon emissions in the transportation sector", etc., indication the direction of green transportation in China.

In China, highway transportation is the mode of transportation that is greatest in terms of energy demand. The energy consumption (mainly electricity) facilities along its route are large and widely distributed, with high total energy consumption, various types of energy demand, and high reliability requirements for some primary load equipment. Margaret Singh et al. [13] introduced the VISION model developed by the U.S. Department of Energy (DOE), and used it to assess the technologies of advanced light- and heavy-duty vehicles, and the potential impact of energy use, petroleum use, and carbon emissions of alternative fuels by 2050, and to evaluate the energy and carbon emission for different highway and traffic scenarios and their comparisons. Shengguo Zhao [14] introduced China's economic situation and energy situation at that time, described the corresponding national policies to promote clean energy development, and provided a proper analysis of future energy issues. Guan Ge [15] systematically analyzed the energy consumption and carbon emission status of transportation in some developed countries and summarized the international transportation green and low-carbon development policies for the current status of energy consumption and carbon emissions of the transportation system in China. Although domestic and international scholars have researched highway transportation energy, they have not yet combined the current status of highway transportation with the latest policy in order to formulate targeted policies. Therefore, this study analyzes the current situation of highway transportation energy integration and the problems of the national transportation and energy development, clarifies the development strategy of highway transportation energy integration with the actual national situation and the goal of sustainable development, and recommends relevant policies.

The rest of the article is structured as follows. Section 2 describes the development needs and problems of green energy highways in China. Section 3 analyzes highway green energy utilization modes, including solar, wind, and other energy sources. Section 4 analyzes the relevant policies for various highway green energy sources. Section 5 describes a solution for the development of green energy for highway transportation. Section 6 gives the conclusion of the paper.

2. China's Highway Green Energy Development Needs and Problems

Highway transportation is an important part of the national economy. Its normal operation ensures the steady development of China's social economy. Highway transportation energy is consumed when transporting materials, people, and information. The rapid development of highway transportation is accompanied by the growth of energy consumption, especially oil products. Sustainable energy development will influence a large part of China's future growth in highway transportation energy consumption.

Following 40 years of reform and opening, China's energy science and technology innovation capacity has reached the world's top tier. China has established an internationally competitive energy equipment technology industry in some areas, which ensures national energy security and supports clean energy and low-carbon transformation. However, there is still a significant gap between China's current capability in energy science and technology innovation and the goal of promoting energy production in the new era and the consumption revolution. This is because there is still a long way to go before an independent and controllable core technology system can be built. The need for clean, efficient energy is now more important than ever, and it is critical to speed up the promotion of the energy technology revolution as China's economy enters the stage of high-quality development [16].

2.1. The Current Situation of China's Highway Green Energy Development

2.1.1. China's Future Transportation Energy Consumption Will Still Grow Rapidly

At present, the amount of energy consumed in the transportation sector accounts for about 10% of the national terminal energy consumption, even if converted according to the common international method. China's transportation energy consumption in 2014 was 430 million tce, accounting for 13.7% of the proportion of the terminal energy consumption of the entirety of Chinese society [17]. In developed countries, the proportion of terminal energy consumption accounted for by transportation energy consumption is usually between 20% and 40%. With the economic development and improvement of living standards, it is inevitable that the proportion accounted for by transportation energy consumption in the whole society will increase, becoming the most significant area of growth in energy consumption. From the viewpoint of per capita transportation energy consumption, the gap between developed countries is more obvious, as the per capita transportation energy consumption of major developed countries is above 0.6 tce. In comparison, China's per capita transportation energy consumption in 2010 was only 0.16 tce, which is less than 1/13 of the per capita transportation energy consumption of the United States.

Supposing that the current development trend continues, with a greater population clustering in large cities and the eastern coast and no breakthrough in industrialization transformation and upgrade. In this case, transportation turnover will grow exponentially to meet the transportation demand of merchandise, people, energy, etc. In the reference scenario, by 2050, cargo turnover will grow 3.9 times, passenger turnover will grow 4.9 times, and private car ownership will grow 5.9 times. Transportation structure continues to develop according to the previous pattern, and the low share of energy-efficient transportation modes, such as railways and waterways, will not be fundamentally improved. At the same time, transport efficiency will continue to improve. In particular, the use of electric and natural gas vehicles and vessels will optimize the transport energy structure to some extent. In these general contexts, transportation energy demand will grow rapidly, and oil demand and carbon emissions will continue to increase [18,19].

2.1.2. The Growth of Energy Consumption in Transportation Poses a Great Challenge to the Security of the Energy Structure

If the current transportation development pattern does not change, the transportation oil consumption will reach 1.09 billion tce (equivalent to 7.6 t crude oil) in 2050. Moreover, it is becoming increasingly difficult to stabilize and increase domestic oil production in domestic oil fields. Several studies have shown that China's domestic oil production will remain relatively stable in the longer term, with annual crude oil production stabilizing at around 200 million t by 2030, and decreasing to around 190 million t of crude oil between 2030 and 2050. Supposing domestic oil production is maintained at around 190 million t in 2050, in this case, the external dependence on oil imports will reach 88.0% by then, which is more than 20 percentage points higher than the highest external dependence on oil in the history of the United States (67%). Considering that 3/4 of the world's oil and gas resources are distributed in the Middle East, Russia, and Central Asia, coupled with geopolitical and transmission channel security factors, China's energy security will come under great pressure at such a time. In addition, with the increase in oil dependence, the fluctuation of international energy prices will hugely impact China's economic activities. This will result in greater risks to China's economic security and social stability [20].

2.1.3. China's Transportation Energy Consumption Puts Great Pressure on Sustainable Energy Development

Compared with developed countries, the energy consumption level of transportation in China is low both in terms of end-use energy consumption ratio and per capita consumption level [15]. Still, because transportation's overall carbon emissions are rising, it is essential to develop a low-carbon economy. China's economy and society have developed rapidly, which has resulted in a considerable increase in the volume of freight and cargo turnover throughout society and an increase in the overall amount of carbon emissions caused by transportation. China's energy consumption from highway and waterway transportation alone accounts for more than 30% of the total national petroleum consumption and its products. According to the current trend forecast, reaching the peak of carbon dioxide emissions in the transportation sector will be difficult in 2030. The proposed carbon peak target in 2030 means that China's transportation industry will take on the difficult task of emission reduction in the coming period, so the growth of energy consumption in transportation has placed enormous pressure on China's energy security, regional environmental pollution, carbon emission reduction, etc. Therefore, transportation is an important research area in China for dealing with energy and related environmental issues.

Energy security pressure may be successfully reduced because of the continued low level of transportation energy consumption, indicating that oil products will peak in 2030 and experience slow growth. At the same time, transportation carbon emissions will also peak in 2035, achieving a "decoupling" of transportation development from carbon emissions. Transportation energy efficiency is a significant contributor to enhancing the priority of energy conservation, optimizing the diverse structure, and fulfilling the green and low-carbon energy sustainable development strategy [21].

3. The Analysis of Green Energy Utilization Mode along the Highway

As a result of climatic and environmental changes and the depletion of oil resources, the pursuit of non-polluting and renewable green energy to replace traditional fossil energy has become the principal technical means for China to combat climate change and optimize its energy structure. On 6 August 2021, the Ministry of Transportation issued the "Guidance on Promoting the Construction of New Infrastructure in Transportation" [22]. On 18 January 2022, the State Council issued the "Fourteenth Five-Year Plan" for the development of a modern comprehensive transportation system [23], which outlined the development of green energy as the primary direction for adjusting the energy structure and the construction of a clean, low-carbon, safe, and efficient modern energy system. Developing and using solar energy as the representative of green energy has become essential to ease China's tightening resource restrictions and improve its ecological environment.

3.1. Solar Energy

In certain regions of China, "highway + solar photovoltaic power generation" is feasible [24]. From a technical point of view, the technology of solar photovoltaic power generation products, mainly crystalline silicon photovoltaic cells, is mature and reliable, with a photoelectric conversion efficiency of about 20% or more. As shown in Table 1, China has developed crystalline silicon (monocrystalline and polycrystalline) high-efficiency cells, amorphous silicon thin-film cells, CdTe, CIS, and polycrystalline silicon thin-film cells. The related technology level has improved, and individual projects have reached or approached the international level. Therefore, photovoltaic energy production with on-site storage and grid-connected technology is feasible.

Table 1. Efficiency levels of terrestrial solar cells developed in China.

Battery	Technology	Efficiency (%)	Area (cm^2)
Single-crystal silicon cell			
(PESC)	Passivation emission area technology	20.40	2 × 2
(IPSE)	Inverted pyramid texturing and selective emission region technology	19.79	2 × 2
(MGBC)	Mechanical groove buried gate technology	18.47	2 × 2
(LGBC)	Laser groove buried gate technology	18.6	5 × 5
Conventional Battery	Conventional Technology	14.51	10 × 10
Multicrystalline silicon cells	General + absorbent	14.5 12.5	1 × 1 10 × 10
Concentrated Light (Silicon) Cells	Dense Grid Technology	17.0	2 × 2
polycrystalline silicon thin film solar cells	RTCVD (Inactive silicon substrate)	14.8	1 × 1
Amorphous silicon battery	PECVD (unijunction)	11.2 11.4	1 mm^2 1 mm^2
Amorphous silicon battery modules	PECVD (double knot)	8.6 6.2	10 × 10 30 × 30
Copper indium selenium battery	co-evaporation	8.0	1 × 1
Cadmium telluride battery	galvanic deposit	5.8	3 mm^2

As shown in Figure 1, a solar power system is a system that converts solar energy into electrical energy to supply electrical loads. It consists primarily of solar cells, charge controllers, batteries, inverters (AC systems), and loads that ultimately use electrical energy.

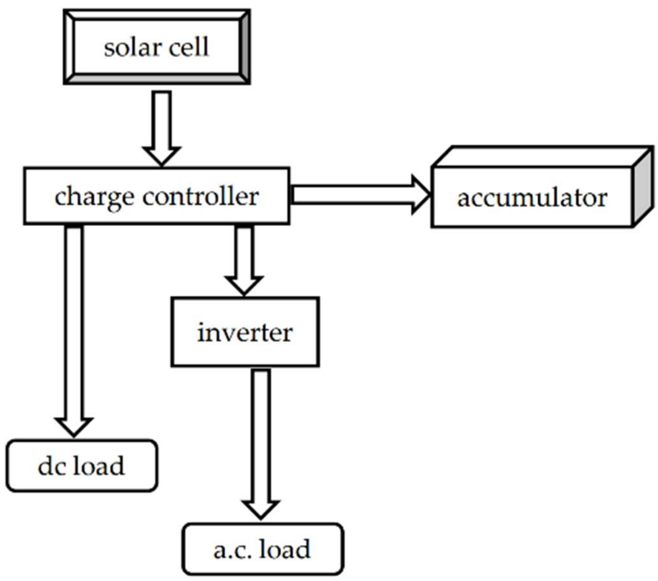

Figure 1. Configuration of solar power system.

From an economic benefit perspective, nearly 20% of China's highway network is located in solar energy class I and II rich resource areas, with favorable conditions for solar photovoltaic development and usage (pilot studies have already been carried out in parts of the class III and IV area highways). Additionally, the project cost of building and utilizing crystalline silicon photovoltaic cells (including the capital cost) has decreased to between 2.5 and 8.0 yuan per watt, making it feasible to expand its use.

Table 2 demonstrates the distribution of China's solar energy resources.

Table 2. Distribution of solar resources in China.

Type Locality	Year Sunshine Hours (h/a)	Annual Radiant All Quality (MJ/m^2 a)	Equal Amount of Heat Required (kg)	Main Areas Included	Remark
I	2300–3300	6680–8400	225–285	Northern Ningxia, Northern Gansu, Southern Xinjiang, Western Qinghai, Western Tibet	The most abundant areas of solar energy resources
II	3000–3200	5852–6680	200–225	Northwestern Hebei, Northern Shanxi, Southern Inner Mongolia, Southern Ningxia, Central Gansu, Eastern Qinghai Department, southeastern Tibet, southern Xinjiang	Areas rich in solar resources
III	2200–3000	5016–5852	170–200	Shandong, Henan, southeastern Hebei, southwestern Shanxi, northern Xinjiang, Jilin, Liaoning, Yunnan, northern Shaanxi, southeastern Gansu, southern Guangdong	Medium region
IV	1400–2000	4180–5016	140–170	Hunan, Guangxi, Jiangxi, Zhejiang, Hubei, northern Fujian, northern Guangdong, southern Shaanxi Southern Anhui	Poor area
V	1000–1400	3344–4180	115–140	Most of Sichuan, Guizhou	Worst area

After the large-scale development and application of "highway + solar photovoltaic power generation" in some areas of China, low-load and low-power facilities' electricity demand can generally be met [25]. Based on the available resources of solar photovoltaic along the highway in China and its estimated amount of total power generation, if solar energy can be developed and used on a large scale in the service areas, side slopes, sound barriers, and tunnel entrances and exits along the highway in solar photovoltaic Class I and Class II regions, the electricity demand of video surveillance cameras, vehicle detectors, lane indication signs, information boards, service area lighting fixtures and air conditioners along the highway and tunnel, air conditioning, and other small power equipment electricity demand can be met (tunnel ventilation systems, enhanced lighting systems, and emergency lighting systems are categorized as high-power primary loads, so generally, the use of solar photovoltaic power supplies are not recommended). Likewise, PV power generation can largely meet the potential electricity demand of facilities along the highway resulting from the development of vehicle–road coordinated autonomous driving technology [26,27].

3.2. Wind Energy

While pursuing economic development in today's world, low carbon emissions, environmental protection and sustainability, and renewable energy are attracting increasing attention in many countries. As one of the most important natural green renewable energy resources, wind energy has advantages including its abundance, solid industrial basis, robust economic competitiveness, and minimal environmental impact. This makes wind energy an important part of renewable energy development. There are abundant wind resources that can be used on the highway, and there is recent relevant domestic and international research on utilizing wind resources on highways [28–31]. Green belts and environmental vegetation have been planted on both sides of the highway, limiting the available space. The specific design should be based on electricity-consuming facilities' actual power supply requirement and the spatial location where the wind turbine may be placed, etc. Small wind turbine power supply systems between 1.0 kW to 10.0 kW and medium wind turbine power supply systems between 10.0 kW to 100 kW can be selected.

The wind power supply system includes a wind turbine, charge and discharge controller, battery pack, inverter, rectifier, etc. As shown in Figure 2, the following parameters need to be determined before constructing the wind power supply system.

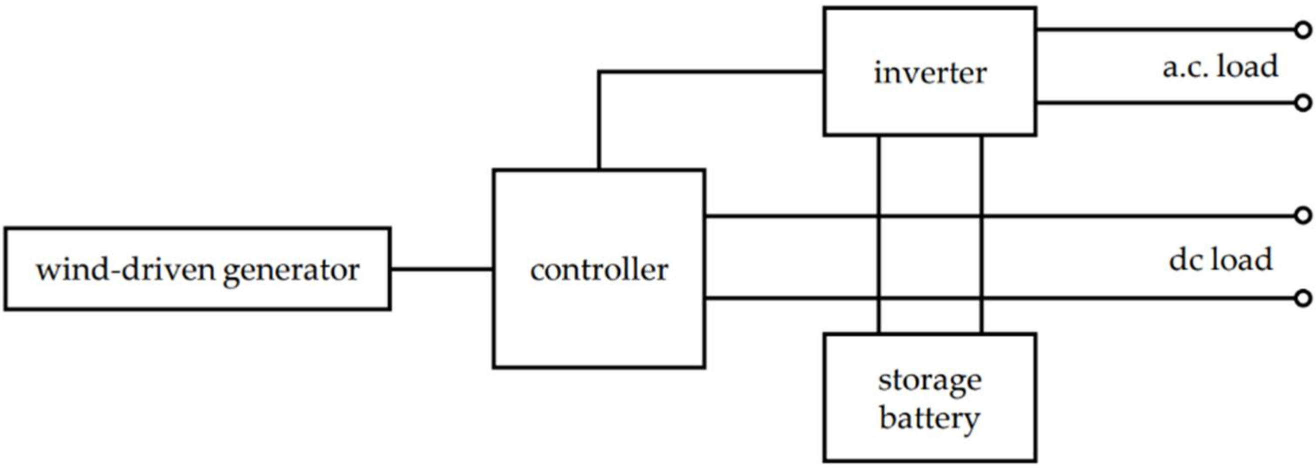

Figure 2. Configuration of wind power supply system.

Complementary wind–solar power supply systems can be utilized in highway locations with abundant wind and solar energy resources. Sind-solar hybrid power systems convert wind and solar energy into electricity. After rectification, inversion, and regulation, the controller converts AC power to DC power, charges the wind–solar hybrid battery pack, and stores electrical energy that is then used to power the facilities along the highway. The combination of wind power with solar photovoltaic power generation can effectively improve the stability of the power supply system.

As seen in Figure 3, the wind–solar complementary power supply system comprises a wind turbine, a solar cell module (square array), a wind–solar complementary controller, an inverter, a battery pack, and other components.

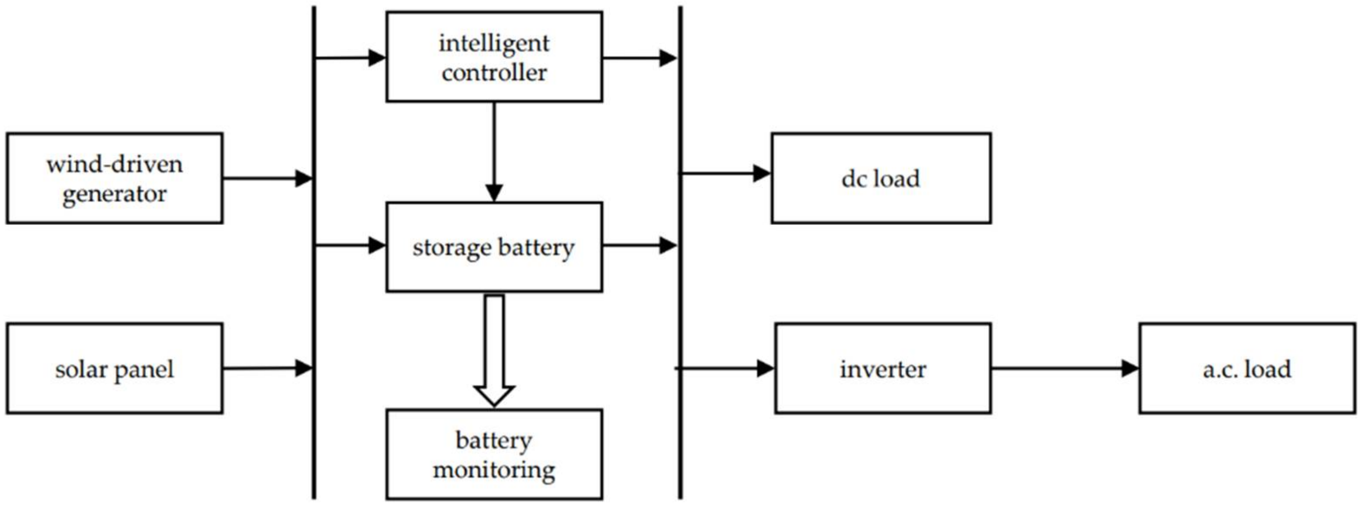

Figure 3. Configuration of the wind–solar complementary power supply system.

3.3. Other Energy Sources

Hydrogen energy, in addition to the above-mentioned solar and wind energy, is a type of secondary energy that is abundant, green, low-carbon, and widely used, and is becoming one of the key drivers of the global energy transition. "Carbon peaking and carbon neutral" (hereafter referred to as "double carbon") is an important strategy in China's social development [32]. Hydrogen energy has gradually become a research hotspot for international and domestic society due to its clean, renewable, and safe features. It is gradually being introduced for use in transportation [33,34] to reduce carbon emissions.

There are three main principles for hydrogen energy utilization: (1) direct combustion; (2) nuclear fusion; and (3) conversion to electricity through fuel cells [35]. The safest and most efficient of these applications is converting hydrogen energy to electrical energy via fuel cells. Direct combustion is currently used mainly in the aerospace area. Direct combustion is also promoted in the metallurgy and automobile areas in the context of "carbon neutrality" and "carbon peaking". Nuclear fusion can release enormous amounts of energy, in which hydrogen nuclei (deuterium and tritium) are combined into heavier nuclei (helium). Thermonuclear reactions or fusion reactions of atomic nuclei are also promising new energy sources today. The nuclei of hydrogen atoms such as hydrogen (protium), deuterium, tritium, and lithium are involved in nuclear reactions and obtain the necessary kinetic energy from thermal motion and then trigger fusion reactions. The detonation of hydrogen bombs is based on thermonuclear processes, which can instantly produce vast amounts of thermal energy. However, it is not yet possible to use it. Controlled thermonuclear reactions can be realized if they can be carried out under control within a certain constraint region according to the will of the people. Fusion reactors are based on controlled thermonuclear processes. Fusion reactors, if achieved, could offer humanity the cleanest and most unlimited energy source. Hydrogen energy is primarily utilized by converting hydrogen to electricity by means of fuel cells. The fundamental principle of the hydrogen fuel cell for electricity production [36] is the reversal of the electrolysis of water, with hydrogen and oxygen being supplied to the cathode and anode, respectively. After hydrogen diffuses outward through the cathode and reacts with the electrolyte, electrons are released to the anode through an external load [36,37]. The main difference between hydrogen fuel cells and conventional batteries is that lithium batteries and accumulators are energy storage devices that store electrical energy and release it when needed. In contrast, hydrogen fuel cells are electrochemical power generation devices that convert chemical energy directly into electrical energy. A hydrogen fuel cell converts chemical energy into electric energy directly without combustion as a kind of power generation device. The energy conversion efficiency can reach 60~80%, with less pollution and noise. The main difference between hydrogen fuel cells and internal combustion engines is that hydrogen fuel cells generate electrical energy through chemical reactions as the power source for transportation, while internal combustion locomotives generate heat energy through combustion as the power source. Since the working process of fuel cells does not involve combustion, there is no mechanical loss or corrosion. The electricity generated by hydrogen fuel cells can be directly used to drive the motor, eliminating the need for a mechanical transmission device in an internal combustion engine. At the same time, long-distance transportation can be achieved by hydrogen refueling.

4. Policy Analysis

The global consensus for the future development of transportation is that it should be safe, efficient, green, intelligent, cost-effective, and low in carbon emissions. As one of the representatives of green transportation modes, highway transportation not only has a more prominent role in supporting and guaranteeing social and economic development, it also faces the huge pressure and challenge of reducing emissions and increasing efficiency in the context of carbon peak and carbon neutral. In recent years, the state has launched a series of policies and programs for highway transportation-related green energy to thoroughly promote highway transportation's green and low-carbon transformation. This study compares and analyzes the existing policies to provide a foundation for developing green energy measures for highway transportation.

In 2021, the Opinions of the State Council of the CPC Central Committee on the Complete and Accurate Implementation of the New Development Concept for Carbon Peaking and Carbon Neutral [10] and the Action Plan for Carbon Peaking by 2030 [38] issued by the State Council pointed out that to integrate carbon peaking and carbon neutral into overall economic and social development, government and industry should take the overall green transformation of economic and social development as a guideline, with energy green, and low-carbon development as the key, in order to accelerate the progress of the transformation of the industrial structure, production mode, lifestyle, and spatial pattern in order to conserve resources and protect the environment, and unswervingly take the high-quality development path of ecological priority and low-carbon to ensure that carbon peaking and carbon neutrality are achieved on schedule. Therefore, transportation can take steps to improve fuel efficiency and promote clean energy to accelerate the carbon reduction process. The transition to low-carbon fuels will play an important role in mitigating climate change in the transportation sector. Meanwhile, highway transportation needs to utilize its renewable energy potential to promote a transition in its energy mix.

In 2022, the Ministry of Science and Technology and nine other departments released the Implementation Plan for Science and Technology to Support Carbon Peaking and Carbon Neutrality (2022–2030) [39], the National Development and Reform Commission and the National Energy Administration released the Opinions on Improving Institutional Mechanisms and Policy Measures for Green and Low-Carbon Energy Transition [40]. The National Development and Reform Commission released "The 14th Five-Year Plan for the Implementation of New Urbanization" [41]. These official documents state that the policy of clean energy substitution in transportation should be improved. Specifically, green and low-carbon transportation transformation should be promoted, the transportation structure should be optimized, and more green and low-carbon transportation facilities and equipment should be implemented. In addition, the clean, low-carbon, safe and efficient use of energy should be promoted, and the consumption of non-fossil energy and the progress of replacing coal with electricity gas should be guided. Distributed energy, such as rooftop photovoltaic energy, should be developed. Clean heating methods such as cogeneration, waste heat heating, heat pumps, and others should be promoted under local conditions. Energy-saving management models, such as contract energy management, should be employed. These policies also support the application of methanol, hydrogen, ammonia, and liquefied natural gas-powered ships and promote the application of sustainable aviation fuels. Meanwhile, alternatives for the electrification of transportation will be strengthened. The construction of fast-charging networks in highway service areas will be promoted, the application of battery-switching will be encouraged, etc. In addition, another study [42] proposed a medium- and long-term development path for the low-carbon transformation of China's transportation. This suggests utilizing the full potential of urban public travel for emissions reduction and promoting vehicle fuel economy and the application of alternative fuel vehicles to support the transportation sector to achieve low-carbon transformation in a technically feasible way.

In June 2022, the Ministry of Transport issued the "Implementation Opinions on Accelerating the Promotion and Application of New Energy Vehicles (Draft for Comments)" [43], and the Ministry of Ecology and Environment and seven other departments issued the "Implementation Plan for Reducing Pollution and Reducing Carbon Synergy" [44]. Both documents mentioned accelerating the development of new energy vehicles, gradually promoting the electrification of vehicles in the public sector, the replacement of old vehicles with new energy vehicles and non-road mobile machinery using renewable energy and clean energy power, and the demonstration and commercial operation of medium- and heavy-duty electric and fuel cell trucks.

4.1. Current Solar Photovoltaic Power Generation Policy

4.1.1. China Strongly Encourages the Development of the Solar Photovoltaic Industry

The 19th Chinese Communist Party Congress clearly proposed clean and renewable energy development. Using green energy, mainly solar, wind, and hydro energy, is the only way to alleviate the problems of China's increasingly scarce resources, environmental pollution, and ecosystem degradation. In 2014, the General Office of the State Council issued the Strategic Action Plan for Energy Development (2014–2020) [45]. This puts forward the low-carbon strategy and the energy structure optimization and uses clean and low-carbon energy as the guideline for adjusting the energy structure. It should be adhered to, in order to improve energy efficiency and reduce the pollution arising from non-fossil and fossil energy. The use of coal should be reduced, and renewable energy such as solar, wind, and geothermal energy should be significantly increased. The proportion of power consumption from nuclear power plants should also be improved. This aims to form a scientific and reasonable energy consumption structure compatible with China's reality, significantly reduce energy consumption and emissions, and promote the construction of an ecological society. This document explicitly put forward "accelerate the development of solar power" and "strengthen the solar power grid service" as requirements for the smooth and secured implementation of photovoltaic power generation.

In August 2020, the Ministry of Transport issued the "Ministry of Transport's Guidance on Promoting the Construction of New Infrastructure in the Transport Sector" [22]. This document states that the construction of ultra-fast charging and high-power electric vehicle charging facilities in urban clusters and other key highway service areas should be guided, and the reasonable layout of photovoltaic power generation facilities along highways such as service areas and side slopes should be encouraged and should be connected to the municipal electricity grid.

In 2022, the Ministry of Transport, the National Energy Administration, the State Grid Co., Ltd., in Beijing and China Southern Power Grid Co., Ltd. in Guangzhou issued the "Action Plan for Accelerating the Construction of Charging Infrastructure along Highways" [46]. This document states that the construction of charging infrastructure along highways should be accelerated to meet the continuously growing demand for electric vehicle charging and serve the public for more convenient commuting. In addition, the strength of all parties should be fully incorporated to promote the electric vehicle industry and accelerate the construction of charging infrastructure along the highway. It is targeted towards the formation of a charging infrastructure network along the highway with the features of "fixed facilities as the main body, mobile facilities as the ancillary body, full coverage of major nodes, high-quality service in operation and maintenance, and satisfying of people's transportation need", to better meet the public demand for high-quality, diversified transportation services.

4.1.2. Reduce Subsidies and Promote Affordable Network Access for Photovoltaic Power

In May 2018, the National Development and Reform Commission (NDRC), Ministry of Finance (MOF), and National Energy Administration (NEA) issued the Notice on Matters Relating to Photovoltaic Power Generation in 2018 [47]. This document mentioned lowering the electricity price for photovoltaic power plants in Class I to Class III resource areas by 5 cents. These resource areas' adjusted electricity prices were RMB 0.5, RMB 0.6, and RMB 0.7 per kWh, respectively. The subsidy rate of the distributed photovoltaic power generation projects using the "self-generation and self-use" model was reduced by 5 cents, from RMB 0.37 to RMB 0.32 per kWh. In January 2019, the National Development and Reform Commission and the National Energy Administration jointly issued the "Notice on Actively Promoting Subsidy-Free Grid Access for Wind Power and Photovoltaic Power Generation" [48]. This document specified that the relevant provincial energy authorities could organize and carry out wind power and photovoltaic power generation projects that do not require state subsidies, considering local resources, consumption capability, and implementation of new technologies. It also put forward several support policies to promote photovoltaic power generation at the beginning of the 14th Five-Year Plan and gradually lower the electricity price.

4.1.3. Improve the Access Threshold and Promote the Solar Photovoltaic Power Generation Industry Upgrade

In July 2017, the National Energy Administration (NEA), the Ministry of Industry and Information Technology (MIIT), and the Certification and Regulatory Commission (CIRC) issued the Notice on Improving Technical Indicators of Major Photovoltaic Products and Strengthening Regulatory Work [49]. This document raised the market access threshold for photoelectric energy conversion efficiency of polycrystalline silicon and monocrystalline silicon cell modules from 15% and 16% in 2015 to 16% and 16.8% in 2018. It also raised the technical standard of the top tier from 16.5% and 17% in 2015 to 17% and 17.8% in 2017. In January 2018, the Ministry of Industry and Information Technology (MIIT) released the PV Manufacturing Industry Specification Conditions (2018 version) [50]. This document put forward more comprehensive and stringent requirements on technical standards of solar PV manufacturers and products in multiple links to eliminate backward production capacity and develop a high-quality and healthy PV industry.

4.1.4. Enhance the Monitoring and Evaluation of the Market Environment

In December 2017, the National Energy Administration issued the Notice on Establishing a Market Environment Monitoring and Evaluation Mechanism to Guide the Healthy and Orderly Development of the Photovoltaic Industry [51]. This is a milestone for photovoltaic power generation, whereby the government also carries out market environment monitoring and evaluation annually, after wind power. The monitoring standard includes two categories, namely, competition evaluation standard and risk evaluation standard. The competition evaluation standard includes land conditions, local government services, national electricity subsidy intensity, local subsidy regulations, etc. The risk evaluation standard includes the situation of solar energy waste and insufficient supply of power, market consumption risk, the completeness of the implementation of the full guaranteed acquisition system, etc. Strengthening the monitoring and evaluation of the market environment helps government departments in industry supervision to achieve early warning, real-time monitoring, and performance evaluation. This is beneficial for optimizing the construction and operation of PV power generation.

In January 2020, the National Energy Administration issued the "Methods and Standards for Monitoring and Evaluating the Market Environment of Photovoltaic Power Generation (Revised Version 2019)" [52], further addressing the decisive role of the market in resource allocation, and monitoring and evaluating the market environment in order to continuously optimize the construction and operational environment of photovoltaic power generation. This also guides the rational investment of enterprises and promotes the sustainable and healthy development of the photovoltaic industry.

4.1.5. Strengthen Photovoltaic Poverty Alleviation

To increase investment in solar photovoltaic poverty alleviation, the pilot-scale project was implemented in around 35,000 documented poor villages across 471 counties in 16 provinces with abundant solar energy resources before 2020. This project took the whole village as a unit. It increased the annual income of 2 million documented poor households with no working labor (including disabled) to more than RMB 3000 per household. Other provinces and cities can select poor areas with good solar energy resources and develop an implementation strategy in accordance with the overall deployment of precision poverty alleviation, specific poverty alleviation requirements, and local conditions. The Ministry of Finance, in the "Ministry of Finance on the issuance of renewable energy tariff surcharge subsidy budget notice" [53], mentioned that RMB 8.1 billion in renewable energy subsidies was issued in 2019, including RMB 37.18 million for photovoltaic poverty alleviation, ensuring that the subsidy for photovoltaic poverty alleviation projects will be paid fully and in a timely fashion.

4.2. Current Status of Wind Power Policy

4.2.1. China Strongly Encourages the Development of the Wind Energy Industry

On 1 June 2022, the National Development and Reform Commission, the National Energy Administration and the Ministry of Finance, and nine other departments issued a notice on the issuance of the "14th Five-Year Plan" renewable energy development plan [54]. This notice vigorously supported the development of wind power. It encouraged improving the local consumption and supply capacity of renewable energy in regions with abundant wind and solar energy resources, superior construction conditions, and the capability of continuous and large-scale development. The regions focused on were Xinjiang, the upper stream of the Yellow River, the Hexi corridor, the big bend of the Yellow River, northern Hebei, Songliao, the renewable energy base in the Yellow River lower stream, and offshore wind power base clusters. Wind power photovoltaic bases will be built using the key electricity transmission channels constructed during the "Fourteenth Five-Year Plan", with the standard being that the portion of renewable energy in new constructions should not be less than 50%. Wind power photovoltaic bases should be planned and built under the instruction of the "Fourteenth Five-Year Plan" with innovative development methods and application models and local consumption capability. The spatial- and temporal-incorporation capability in the regional power grid should be utilized, the regional grid load-shifting capability should be coordinated, the inter-provincial power grid boundary should be broken, and the cooperation of the demand side and the supply side should be strengthened in order to secure the market for large wind power photovoltaic bases.

In general, prioritizing wind power industry clustering is encouraged, while the wind power industry should be decentralized in industrial parks, economic development zones, oil and gas mining areas, and the surrounding areas. The application of low-speed wind power technology should be emphasized. The lands, including barren hills and coastal beaches, should also be utilized. The wind power industry clustering in southeastern China should be implemented based on the local conditions and the regional ecological and environmental protection requirements. Wind power investment and construction mode and land use mechanisms should be further innovated. The "thousands of villages to harness the wind" action should be implemented to promote wind power development in rural areas. The old wind turbines in areas with abundant wind energy resources should be upgraded to improve wind energy conversion efficiency.

4.2.2. Sources of Wind Power Subsidy Funds

The Ministry of Finance announced the "renewable energy tariff surcharge subsidy funds management approach" in January 2020 [55], which indicated the incentive opportunities available for electricity from renewable energy. The full feed-in tariff policy on wind and solar power was implemented.

The electricity price of wind and photovoltaic power should be subsidized based on the size of feed-in power or feed-in tariff. The local renewable energy development fund and grid enterprises should settle the subsidy funds according to the tariff of each grade. The wind power and photovoltaic power projects included in the national plan should be after the approval of the State Council. The subsidy funds and renewable energy tariff surcharge income can be counted as local financial revenue sources.

4.2.3. Wind Power Grid Management

To cope with extreme weather, reduce the grid operating load, and ensure the safe and stable operation of the grid, the National Energy Board issued "On the Work Related to Power Dispatching in 2018" on 27 July 2018. This notification instructed power grid operators to dispatch power efficiently in compliance with the applicable central deployment. Meanwhile, it is required that all local governments and companies should play the role of power dispatching, especially combining the actual regional situation to adjust the relevant grid operation mode and wind power operation mode to ensure the safe and stable operation of the grid and the reliable supply of electricity.

The full implementation of the transmission line channel capacity building project approval system reformation was begun on 16 May 2019. This requires changing the cross-region transmission channels from approval-based to recorded- and listed-based (recorded-based). The consumption of new energy generation should be improved, and the marketization progress of wind power and the construction of cross-region transmission channels should be promoted. The reformation and innovation of power grid operation should also be encouraged. The responsibility for the safe and stable operation of the power grid should be strictly implemented, and the working mechanism, accountability system, and emergency disposal mechanism should be established and improved.

4.3. Current Hydrogen Power Generation Policy

4.3.1. China Strongly Encourages the Development of the Hydrogen Energy Industry

Hydrogen energy is a type of secondary energy with an abundant source, is green and has low carbon emissions, and is employed extensively. It is crucial for constructing a clean, low-carbon, safe, and efficient energy system and attaining carbon neutralization. The Opinions of the CPC Central Committee and the State Council on the Complete and Accurate Implementation of the New Development Concept to Achieve Carbon Neutrality [10] require the development of the whole chain of hydrogen energy, including "production, storage, transmission, and use". The construction of hydrogen refueling stations and the research and development of cutting-edge low-carbon technologies, such as hydrogen production from renewable energy, should be promoted. The key technologies, research, and development pilot and large-scale hydrogen energy production, storage, and application projects should be strengthened. The Notice of the State Council on the Issuance of the Action Plan for Carbon Peaking by 2030 [56] clearly states that the research and development and the pilot project of hydrogen energy technology should be accelerated, and the application in industry, transportation and construction fields should be explored and implemented in large-scale. In March 2022, to promote the standardized, orderly, and high-quality development of the hydrogen energy industry, the National Development and Reform Commission and the National Energy Administration issued the "Medium- and Long-term Plan for the Development of Hydrogen Energy Industry (2021–2035)" [57]. This categorized hydrogen as a component of the future national energy system. It encouraged using the clean and low-carbon characteristics of hydrogen energy to promote the green and low-carbon transformation of transportation, industrial, and other high-energy-consuming and high-emission sectors. It also proposed the goals of each stage of the hydrogen energy industry. By 2025, the core technology and manufacturing process should be developed, the number of fuel cell vehicles should reach 50,000, hydrogen refueling stations should be deployed and constructed, the hydrogen produced from renewable energy should reach 100,000–200,000 tons, and CO_2 emissions should be reduced 1–2 million tons per year. By 2030, a more complete hydrogen energy industry technology innovation system, green hydrogen production, and supply system should be formed to support the carbon peak target's achievement strongly. By 2035, a diversified application ecology of hydrogen energy should be formed, and the proportion of green hydrogen in end-used energy consumption should be significantly increased.

The State Council issued two consecutive policies on 15 December 2022, to support the development of hydrogen energy facilities. The Central Committee of the Communist Party of China (CPC) and the State Council issued the Outline of Strategic Planning for Expanding Domestic Demand (2022–2035) [58], which ordered the release of the consumption potential of hydrogen in the transportation sector. The layout of urban transportation networks should be optimized, and intelligent transportation should be vigorously developed. The transition of automobile consumption from purchase management to use management should be promoted. The electrification, networking, and intelligence of automobiles should be strengthened. The construction of charging piles, hydrogen refueling stations, and other supporting facilities should be improved. Subsequently, the 14th Five-Year Plan for Modern Logistics Development [59] was issued, pointing out that the construction of charging piles for trucks, hydrogen refueling stations, and shore power facilities for inland vessels should be strengthened. The application of hydrogen and other clean energy should be actively expanded in its transportation, storage, and distribution to accelerate the supply and refueling system of natural gas, hydrogen, and other clean energy.

4.3.2. Complete Hydrogen Energy Evaluation Standards

To promote the high-quality development of China's hydrogen energy industry and implement the "carbon peaking and carbon neutral", the "Standard and Evaluation of Low Carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen" proposed by the China Hydrogen Energy Alliance was officially released on 29 December 2020.

This is the first time carbon emissions from hydrogen have been quantified as a standard worldwide. Using the life cycle assessment approach, the standard establishes quantitative norms and an evaluation methodology for low-carbon, clean, and renewable hydrogen. It fosters the green development of the entire hydrogen energy supply chain. The standard points out that in terms of carbon emissions per unit of hydrogen, the threshold value for low carbon hydrogen is 14.51 k CO_2e/kgH_2, while for clean hydrogen and renewable hydrogen it is 4.9 $kgCO_2e/kgH_2$, where the renewable hydrogen requires that the energy source for hydrogen production is also renewable energy.

In 2022, the "Implementation Plan for Establishing a Sound Carbon Dumping and Carbon Neutral Standard Measurement System" [60] was issued by nine departments, including the State Administration of Market Supervision. This document aims to promote the development of green hydrogen production standards, such as generating hydrogen via electrolysis using renewable energy. It also develops hydrogen storage standards such as high-pressure gaseous hydrogen storage, solid hydrogen storage systems, and liquid hydrogen storage tanks. The pipeline hydrogen transportation (hydrogen blending), medium and long-distance hydrogen transportation technology and equipment, and hydrogen transportation standards should also be promoted. On 12 October, the State Administration of Market Supervision and Administration and the National Standardization Administration released the national standard GB/T 31138-2022 "Hydrogen Refueling Machine".

5. Countermeasures of Highway Transportation Green Energy Development

Based on the above analysis, the development of green energy for highway transportation should be combined with China's regional transportation energy demand, solar photovoltaic, wind energy, and other natural resources to construct a green self-consistent energy transportation infrastructure supply network and achieve the self-consistent use of the distributed green energy by utilizing transportation infrastructure.

The 19th Chinese Communist Party Congress proposed vigorously developing clean, renewable energy and promoting the energy production and consumption revolution. As an essential component of renewable energy, the vast natural resources of green energy on highways are consistent with the national strategic development goal.

This study suggests that highway transportation and green energy growth should concentrate on one core objective, two major roles, and five major security systems.

5.1. One Core Objective

The core objective is to utilize natural resources for highway transportation infrastructure. The new strategic idea of green energy for transportation should be followed. Under the objectives for high-quality transportation development, the problem of the unbalanced and insufficient distribution of China's transportation infrastructure and energy demand should be resolved. Green energy from natural resources of highway transportation infrastructure should be utilized. These aim to support the green energy development of highway transportation.

5.2. Two Major Roles

The two major roles include the government serving as the guide and enterprises serving as the main executors. On the one hand, the government makes policies for the transportation industry to enhance public services and create a favorable environment; on the other hand, enterprises can be stronger and better to support the guidance of a "country with a strong transportation network". The development of higher efficiency, better quality, lower costs, and more motivation for industries can be promoted.

5.3. Five Major Security Systems

5.3.1. Improve Regulations and Standards

Improving regulations and standards aims to strengthen the leadership of regulations and standards. The revision of relevant laws and regulations should be accelerated based on the existing legal system, and relevant departmental regulations should be completed and improved. The development of the national, industrial, local, group and enterprise standards should be coordinated and promoted to support the development of transportation and green energy enterprises.

5.3.2. Guiding Personnel Training

Guiding the personnel training will improve the personnel quality in business management and accelerate the progress of training many entrepreneurs and professional managers with a global vision and international management ability. A modern transportation vocational education system should be built, and laborers who are highly skilled and familiar with both new and traditional technologies should be trained. AN incentive mechanism for innovative professionals in the transportation industry should be established and improved to form several international and innovative professional teams, thereby motivating the construction of a world-class transportation industry. It should stick to the principle of integrity and continuously enhance the quality of products and services to provide qualified customer service.

5.3.3. Demonstrate and Promote the Key Pilot Projects

This guides the highway and energy-related industry associations and local organizations to carry out special actions such as technology demonstrations. Several domestic and international key projects should be chosen as benchmarks, and the gaps and weaknesses against the benchmarks should be found and constantly improved to catch the top tier. Several star industries in a "country with a strong transportation network" should be created and demonstrated. The advanced experience and practices should be promoted through the preparation of case sets, meetings for experience exchange, enterprise field meetings, and other forms.

5.3.4. Increase Financial and Tax Support

The structural tax exemption policy to support enterprise development should be actively implemented. The financial support methods should be innovative and gradually change from "subsidizing construction" to "subsidizing operation" to improve the efficiency of using existing transportation financial funds.

5.3.5. Strengthen Financial Security

Financial institutions and other departments should be coordinated to provide medium- and long-term financial support for scientific and technological innovation and transformation and upgrading in transportation and energy. The financial institutions should be guided to actively develop liquidity loan products that meet the transportation industry's requirements. Financial products and services should be developed to boost the capital market and give financing support to transport enterprises so that they may become more competitive globally.

6. Conclusions

Based on the issues of China's highway transportation energy development, this study analyzes the current challenges of green energy utilization in conjunction with China's policies. It proposes a model and development pathways for highway transportation and green energy utilization.

6.1. Formulate Top-Level Planning and Increase Industry-Specific Policy Support

As the carrier of green energy development and utilization in the highway transportation industry, consisting of highways, service areas, transportation hubs, freight yards, etc., with the characteristics of multiple places and large areas, distributed power generation is the superior solution. Nonetheless, dispersed power stations now adhere to the "one location, one project firm, one record" development model, making it difficult to quantify the scale and systematic benefits of such small-scale and distributed power generation. The relevant departments should work together to introduce relevant policy documents or action plans to promote the use of green energy in highway transportation and propose the overall planning, implementation scale, and technical requirements for the use of green energy in highway transportation [61].

6.2. Classify and Promote Highway Green Energy Demonstration Projects

This incorporates existing mature technologies into the technology promotion catalog of relevant departments and analyzes and establishes the planning program for developing and utilizing natural highway green energy resources. The green energy of highway transportation should be implemented into pilot projects of relevant ministries and commissions to enhance the level of green energy of highway transportation.

6.3. Study and Develop the Highway Transportation Green Energy System Standards

This utilizes highways, service areas, transportation hubs, and freight yards as research carriers to develop product standards and engineering specifications. This provides a technological foundation for the pilot project development for green energy generation to raise the technical level and application scope.

Lastly, it should be mentioned that even though highway power generation is a distributed linear project, the size of the power generation system is small and can be constructed according to actual needs. The options for construction areas can be wider, and there is a great deal of space for growth in developing comprehensive energy usage. However, because the efficiency of power generation and usage is not as great as that of centralized systems, further research is required to determine how to use it more efficiently.

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