

Development Strategy for Energy System of Land Transport in China

Yang Yongping, Wu Ping, Cheng Peng, Shi Ruifeng, Tian Xinshou

China Institute of Energy and Transportation Integrated Development, North China Electric Power University, Beijing 102206, China

Abstract: Considering the high-quality development of the energy sector in China, the integration of the energy and transport sectors can facilitate the low-carbon, high-efficiency, and intensive development of both sectors and contribute to carbon peaking and carbon neutralization. This study reviews the development status and trends of energy systems for land transport and proposes a novel system architecture comprising of power, physical, and application levels. Three integrated scenarios—interconnected power grid, electrified transportation, and energy-transport integrated network—were analyzed from energy-dominated, transport-dominated, and energy-transport integrated perspectives. Moreover, a novel development strategy for land transport energy systems is proposed based on the potential evaluation of natural resources available for transport energy systems on highways and high-speed railways. A development strategy consisting of three structures, three scenarios, and three driving forces is proposed to guide the construction of a low-carbon and efficient transport infrastructure. Innovation directions for the transport energy system include key equipment research and development, construction and maintenance of the integrated system, and the formation of technical specifications and standards. Therefore, it is essential to promote a modern transportation energy system that is dominated by renewable energy and supported by electric power. Furthermore, a new transport power system that integrates renewable energy generation, zero-carbon fuel, and electric drives should be established, and a transport–energy-integrated infrastructure should be planned and constructed.

Keywords: land transport; transport energy system; interconnected power grid; electrified transportation; energy-transport integrated network

1 Introduction

The evolution of transportation has experienced shifts from animal power to coal, oil, and other forms of energy, each transition inextricably linked with a transformation in energy sources. The amalgamation of biomass energy with animal-powered transportation facilitated the emergence of agricultural civilization. Similarly, the integration of steam engines with fossil energy heralded the onset of the first industrial revolution, while the pairing of motor vehicles with electrical power fueled the progression of the second industrial revolution. Currently, transportation accounts for approximately two-thirds of the world's oil consumption, with the associated carbon emissions contributing to roughly a quarter of the global total, exacerbating the worldwide greenhouse effect [1,2]. As transportation continues to expand, it is essential for its energy systems to transition from fossil fuels to renewable sources, thereby achieving a zero-carbon system [3–5].

As China's economy and society progress, land transportation, a vital facet of logistics, continues to see expanding energy consumption. Given the strategic objectives of realizing peak carbon emissions and subsequent carbon

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Corresponding author: Cheng Peng, associate research from the China Institute of Energy and Transportation Integrated Development, North China Electric Power University. Major research fields include new-energy transportation system and new-energy power system. E-mail: p.cheng@ncepu.edu.cn

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neutrality, it has become particularly urgent to construct a new land transportation energy system primarily powered by renewable energy. Evaluating both domestic and international transportation energy systems [6–8], it is clear that transportation systems possess ample natural endowments. This is especially true in western China, where land transportation is readily available. It is crucial to fully utilize these natural resource endowments to establish an energy supply system that caters to the operational and maintenance requirements of transportation. This type of a system would not only enhance the level of independent energy security for transportation and optimize the structure of transportation energy, but also create an independent energy supply in areas where transportation and energy are accessible. This would ensure uninterrupted traffic operations through the new system. For instance, the natural endowments of solar energy along China's highways and high-speed railways amount to 1.023×10^{12} kW·h and 2.396×10^{11} kW·h, respectively. By fully exploiting these natural resources, we can satisfy the energy requirements of land transportation and improve the self-sufficiency of transportation energy [8,9]. Based on the standpoint of electrified railway energy supply, the structure and implementation strategy for a traction power supply system that allows new energy access to electrified railways have been proposed. The flexibility and reliability of the electrified railway traction power supply can be enhanced by incorporating energy units such as new energy generation and electrochemical storage [10–12]. With respect to highway energy, the trend toward electrification is unmistakable, validating the feasibility of large-scale electric vehicles participating in vehicle–grid interactions and their role in strengthening the capacity of energy and electric power systems [13–15]. Therefore, as a major energy consumer, the land transportation system will continue to explore its internal energy supply capacity, a critical aspect in optimizing the transportation energy structure and fostering a green, low-carbon, and environmentally friendly transportation energy system.

Considering the goals of reaching peak carbon emissions and achieving carbon neutrality, the transportation industry is under significant pressure to reduce carbon emissions. To encourage such reductions in China's land transportation sector, there is a clear need to establish a new transportation energy system, primarily powered by clean energy. Responding to this requirement, this study proposes a construction plan for a land transportation energy system, drawing insights from both domestic and international advancements in transportation energy systems. Using highways and high-speed railways as examples, we explore and evaluate the potential of natural resource endowments for the proposed land transportation energy system, outlining essential conditions for the system's construction. Moreover, this paper presents a development strategy and suggests innovative directions for the land transportation energy system, intending to provide a foundational reference for both theoretical and applied research in the field of new transportation energy systems.

2 Development trend of the land transportation energy system

2.1 Current status of land transportation energy system

Currently, numerous instances exist where renewable energy is combined with rail and road transportation, showcasing the immense potential for the integrated development of energy and transportation. This integration not only enhances the utilization of transportation land resources, but it also encourages the consumption of renewable energy, lowers carbon emissions, and facilitates the harmonious development of the energy and transportation industries.

Currently, more than 10% of the power consumed by Germany's electrified railways is derived from solar, wind, water, and other renewable energy sources. A demonstration project is underway to connect a megawatt photovoltaic power generation system directly to the 16.7-Hz AC electrified railway traction power supply system, with the anticipation of achieving zero-carbon railway operations by 2050 [16,17]. The Rotterdam Central Railway Station in the Netherlands has been transformed into the largest rooftop photovoltaic project in Europe, boasting an annual power generation of up to 3.2×10^5 kW·h [18]. The East Japan Railway Company has developed a 453 kW·h distributed photovoltaic power generation project at the Tokyo Railway Station, providing traction power for rail transit [19]. A UK-based demonstration project has constructed a photovoltaic power system connected to a DC traction power system. Each megawatt solar power generation device in this system can reduce carbon emissions by approximately 245 t per year, thereby promoting clean and self-sustaining railway traction energy consumption [20]. In terms of rail vehicles, hydrogen-powered trains have made significant strides [21]. For instance, the modern tram demonstration line in the Gaoming District of Foshan City, Guangdong Province, uses hydrogen-powered trams for operation. Similarly, since 2018, Lower Saxony in Germany has utilized hydrogen-powered trains, manufactured by Alstom, France, for regional passenger transportation.

Leveraging the swift advancement of new energy vehicles for highway transportation, integrated charging stations that combine solar, storage, and charging have been widely implemented [22–24]. In 2015, solar panels installed on highway slopes in the United States generated 99 kW of power [25]. In 2016, the world's first photovoltaic road, spanning approximately 1 km, commenced operation in northwestern France. Italy constructed a solar wind bridge that integrates transportation, landscape, and green energy, using densely placed solar panels on the deck and wind turbines between pillars. This structure produces approximately 4×10^5 kW·h of power annually [26]. In 2020, a distributed photovoltaic power generation project in the highway service area of Shanxi Province was launched, boasting a total installed capacity of 395 kW and an annual generation capacity of approximately 6.5×10^5 kW·h. This system, employing the “car-shed photovoltaic + rooftop photovoltaic + ground photovoltaic” mode, realizes environmental benefits via energy conservation and emission reduction [27].

2.2 Prospect of land transportation energy system

The rapid advancement of the energy and transportation industries has significantly strengthened the interconnection and integration of these two sectors, thereby providing a prerequisite for the transformation of the land transportation energy system.

In contemporary China, renewable power is extensively utilized. Both wind power and photovoltaic power generation are progressing rapidly. In 2021, the cumulative grid-connected scale of wind power generation and photovoltaic power generation reached 3.3×10^8 kW and 3.1×10^8 kW, respectively. By 2030, the grid-connected scale of wind and solar power is projected to exceed 1.2×10^9 kW. This development provides clean and decarbonized energy assurance for the construction of a new power system established on renewable energy, ensuring the sustainable growth of the economy and society [28]. Simultaneously, the creation of a comprehensive modern transportation system characterized by “safety, convenience, efficiency, green technology, and economic viability” has emerged as a trend, with noticeable progress in clean transportation energy consumption and power electrification. For instance, in 2020, the number of pure electric new energy vehicles in China amounted to 4×10^6 [29], and the operating mileage of electrified railways reached 1.063×10^5 km [30]. Under the goals of achieving peak carbon emissions and carbon neutrality, substantial changes in energy and transportation are inevitable. This will catalyze the development of innovative models and technologies, thereby enabling the transformation and advancement of clean energy, green transportation, and sustainable development. This progress is driven by energy security concerns and the strategy of building China's strength in transportation. Promoting the transformation and development of the land transportation energy system represents an innovative collaborative practice between transportation and energy sectors. It is an essential pathway to support green development in line with the strategy for achieving peak carbon emissions and carbon neutrality.

From a developmental paradigm perspective, acute challenges, such as resource shortages, climate change, and environmental pollution, exacerbated by existing emissions and development modes lacking synergism, threaten the sustainability of social development and economic growth in China. Green development-oriented strategic planning, industrial transformation, and upgrading have become essential approaches and key policy priorities. The necessity of shifting energy-related schemes and reforming the supply side is a natural outcome of policy choices and the response to requirements posed by the development of green and intelligent transportation. This transition urgently demands top-tier design and collaboration between the transportation and energy sectors [31–33]. In the global context of energy conservation and emission reduction, the domestic commitment to promoting sustainable development is fundamental. Establishing the basic structure of energy and transportation integration, and re-evaluating the structure and form of land transportation energy systems under the new development pattern will play a positive role. This will aid the construction of energy networks, the electrification of transportation power, and the transition to cleaner energy use.

From an economic construction perspective, in the context of the dual circulation of domestic and international markets, and given carbon peaking and carbon neutrality goals, high-quality development has become the central theme of economic and social advancement in this new era. Energy and transportation, as fundamental drivers of economic growth and societal function, directly influence the patterns, forms, and quality of economic development [34,35]. Thus, the reform of the land transportation energy system will lead to a rise in new technologies, business models, industries, and practices, further stimulating industrial restructuring and growth. Moving forward, energy and transportation will transition from fragmented and isolated development toward a model of coordinated progress. This shift will encourage efficient collaboration between energy and traffic flows, underpinned by a comprehensive transportation infrastructure system that is clean, low-carbon, and efficient. The reform of the land transportation

energy system is a necessary trend to expedite the energy revolution and transportation transformation, fostering sustainable economic and social development. It will enhance the low-carbon development levels of the energy and transportation sectors and support the realization of national carbon peaking and carbon neutrality goals, bolstering our decarbonization competitiveness.

3 Construction of land transportation energy system framework

3.1 System architecture

Guided by the principles of “innovation, coordination, green, openness, and sharing,” there have been substantial improvements in the operational efficiency of the energy and transportation industries. The energy consumption structure has shifted toward cleaner alternatives, and convergence features are becoming increasingly prominent. (1) The evolution of the energy industry is illustrated in three primary areas: the move toward clean energy generation, indicating a transition from high to low carbon; the electrification of energy consumption, with an increasing proportion of end-use energy consumption coming from electricity; and a broad distribution of energy allocation, where the development of renewable energy is gradually moving from large-scale grid connections to centralized grid connections and distributed access. (2) The key features of the transportation industry’s evolution are demonstrated in three respects. The first aspect is the clean energy use for the sustainable development of the transportation system; widespread use of alternative energies such as electricity and hydrogen helps reduce the transportation industry’s reliance on fossil fuels such as oil, consequently lowering the transportation system’s carbon emissions. The second aspect is power electrification as a means to enhance the energy efficiency of the transportation system; with the rise of clean energy use patterns, electric motors will replace internal combustion engines as mainstream power equipment, and comprehensive electrification is the overall trend. The third aspect is that system integration serves as a vital measure to achieve efficient and intensive operation of the transportation system. Effective coordination and linkage of transportation channel resources and natural endowments can heighten the utilization rate of transportation land space, decrease construction costs, and enhance the functionality of transportation hubs.

Overall, the energy and transportation industries are converging toward a clean, efficient, and integrated direction of development. Their intrinsic connections are deepening, and they are leading in integrated applications in areas such as smart energy and autonomous transportation. This study proposes a framework for China’s land transportation energy system (Fig. 1), comprising of three layers: (1) The power layer is an energy system that supports the operation of energy and transportation systems, primarily utilizing oil, natural gas, electricity, hydrogen, and other forms of energy. This layer provides power for the operation and maintenance of equipment and facilities in the physical layer. (2) The physical layer includes all types of equipment and terminals of the energy and transportation system. As the physical carrier of the power layer, it encompasses substations, passenger and freight hubs, and carriers, providing operational support for the execution of business and services within the application layer. (3) The application layer incorporates various business services of energy and transportation systems. Functioning as a platform for value creation, it entails planning, construction, operation, and maintenance, as well as energy charging, power supply, and other businesses and services.

3.2 Systematic morphology

3.2.1. Interconnected power network

The interconnected power grid, with a focus on transportation infrastructure and the power layer, harnesses the resource endowments within transportation infrastructure. In the initial phase, renewable energy is utilized for electricity generation, supplying clean energy to the transportation system. In the subsequent phase, the fuel for transportation equipment is produced through hydrogen obtained from electrolytic water and synthetic ammonia, keeping in line with the requirements of transportation equipment. Electric power, as a clean, efficient, and convenient form of secondary energy, leads the integrated development of the power layer in land transportation energy systems. This approach cultivates transportation assets for energy utilization and, in combination with electric power technology and information technology, establishes a clean, efficient, and integrated interconnected power network for energy production and distribution through energy integration modes. Taking the smart grid as the primary element, complete integration of the energy and transportation power layer is realized, providing a clean, efficient, and independent power guarantee for energy and transportation systems.

A prominent feature of the interconnected power grid’s integration is its power-centric approach, aiming to unify

the production and usage within the land transportation energy system. This system capitalizes on the spatial resources of the transportation infrastructure, realizing an effective amalgamation of energy production and utilization facilities via the energetic development of transportation infrastructure assets. The energy load of the transportation infrastructure also creates a broad scope for renewable energy consumption, thereby mitigating instances of abandoned wind and solar power. For these types of modes of transportation energy integration, our focus is on fortifying the connection and amalgamation between the power network and transportation energy system. This facilitates an accelerated transition toward clean power substitution, enhancing the overall efficiency and cleanliness of the energy systems.

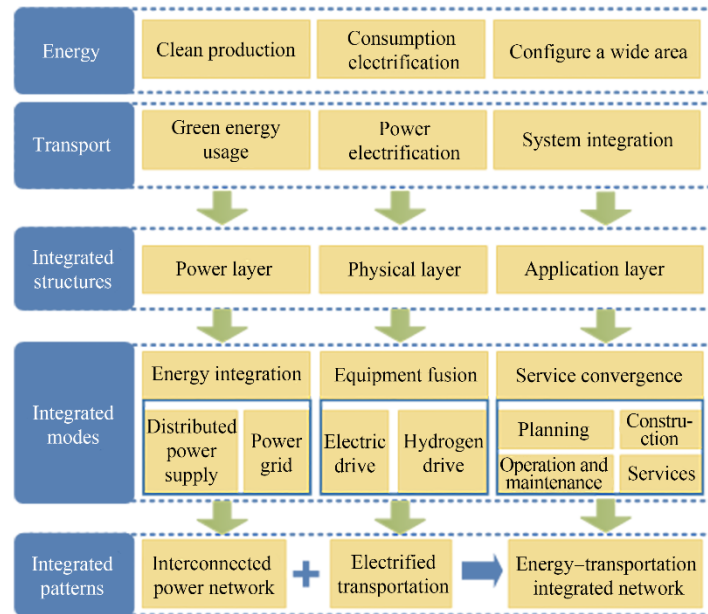


Fig. 1. Framework for China's land transportation energy system.

3.2.2 Electrified transportation

Electrified transportation emphasizes transportation equipment, or the physical layer, and ushers in an innovative evolution of the transportation equipment power system. This transformation upgrades the original petroleum-based power system to one rooted in clean energy sources such as electrochemistry, hydrogen, and ammonia, consequently reducing the carbon emissions of transport equipment. Electrified transportation, which replaces traditional fossil energy with electricity as the power source for carrier equipment, is a pivotal trend in the quest for transportation energy conservation and emission reduction. It will steer the integrated development of the physical layer within land transportation energy systems. Directed by the transformation and upgrading of transportation power sources, and in conjunction with modern manufacturing technology and power electrical technology, an efficient and low-emission electrified transportation pattern is formed. Considering transportation equipment as the main body, this electrified transportation stands as a crucial node for the integrated development of energy and transportation systems. As an energy terminal, the corresponding clean and low-carbon process depends on the power supply quality of the energy system. As a new transport tool, it directly determines the energy utilization efficiency of transport equipment.

The prominent characteristic of electrified transportation is its reliance on electric energy as the power source. This strategy aims to achieve high-efficiency energy use for transportation equipment by replacing traditional fossil energy with electric energy, thereby facilitating a clean and efficient transformation of vehicle power. As hydrogen energy technology continues to advance rapidly, hydrogen-powered transportation has emerged as an effective supplement. This solution is poised to overcome the limitations of lithium battery range and recharge time, and further promote deep decarbonization of the transportation system. With such an energy integration model for transportation, our focus is on enhancing the integration of electric energy, hydrogen energy, and transportation equipment power. This integration plays a crucial role in consuming clean energy, improving power efficiency, reducing carbon emissions, and more.

3.2.3 Energy-transportation integrated network

The energy-transportation integrated network is centered around the convergence of transportation and energy at

the business level, leveraging the natural resources of the transportation system to produce zero-carbon transportation fuel. This approach aims to satisfy the power needs of transportation equipment, and it will form a new transportation energy integration system that unifies energy capture, fuel production, and transportation refueling.

The energy–transportation integrated network actualizes the integration of the application layer within the land transportation energy system. This is realized through the coexistence of energy and transportation networks, wherein various forms of energy and electric transport are processed concurrently. Furthermore, all forms of energy supply, such as electricity and heat, can be directly interconnected or interacted through the corresponding converter, bypassing the need for an electricity-centered conversion link. Under this model, the energy and transportation systems are collectively planned, featuring the construction of micro energy network units and independent transportation operations. Based on the production and utilization requirements of various energy sources, we construct a self-sufficient energy system for transportation that is coupled with electricity, hydrogen, cooling, heating, and other forms of energy. This promotes the integration and connection of energy production and use, transportation, and travel applications.

The prominent characteristic of the integrated form of energy and transportation networks is the coexistence of energy power grids and electric transportation networks on an equal footing. This arrangement aims to achieve comprehensive supply and distribution of multiple forms of energy along with self-contained transportation energy. This approach breaks down the industry barriers between energy and transportation systems, fostering collaborative construction of channels, hubs, and terminals while facilitating deep integration of their respective operations. As a novel type of networked infrastructure, the energy–transport integrated network carries the attributes of both energy and transportation networks. This form of land transportation energy system provides superior resource allocation and stronger autonomous guarantee capabilities. It represents a vital pathway toward enhancing the efficiency of energy utilization and transportation operations.

4 Evaluation of the potential of land transportation energy system: considering photovoltaic asset potential as an example

The adaptable modules and simple installation characteristics of photovoltaic power generation make it an apt pairing with land transportation infrastructure, paving the way for a clean and efficient self-sufficient transportation energy system. This study specifically addresses resources linked with land transportation routes, such as expressways and high-speed railways. We propose integration strategies for photovoltaic power generation that capitalize on the energization of transportation assets. We use the Beijing–Shanghai Expressway, Beijing–Harbin Expressway, Beijing–Shanghai High-Speed Railway, and Beijing–Harbin High-Speed Railway as examples to conduct a detailed potential assessment.

4.1 Evaluation model of transportation infrastructure energy potential

For highways, the available land for photovoltaic implementation primarily includes roadside spaces and service area spaces. These comprise roadside slopes, side ditches, and exclusive space above the road; while service areas include building rooftops, parking lots, and access ramps. To objectively evaluate the potential for energizing highway assets with photovoltaics, this study uses 70% of the available space as the calculation benchmark. Regarding high-speed railways, the available land for photovoltaic installations primarily includes spaces along the railway and within station premises. The former includes slopes on either side of the tracks and dedicated spaces for tracks, while the latter includes station rooftops, squares, parking lots, and canopies. To objectively assess the potential for energizing high-speed railway assets with photovoltaics, this study considers 70% of the total area—which includes a 10-m space resource on both sides of the line, railway station roofs, squares, parking lots, and canopies—as the calculation benchmark. The model used to assess the exploitable photovoltaic potential is displayed in Fig. 2.

4.2 Self-contained rate evaluation of energy consumption on transportation infrastructure

To assess the degree of energy self-sufficiency achieved through the energization of transportation infrastructure assets, this study introduces three indicators: total self-containment rate, transient self-containment rate, and power-shift rate. These indicators, as illustrated in Fig. 3 [8], are employed to analyze the energization potential of infrastructure assets and power load of infrastructure in representative scenarios. By considering the Beijing–Shanghai Expressway in North China–East China and Beijing–Harbin Expressway in Northeast China as examples, this study showcases the development potential of expressway asset energization. Additionally, by considering the

Beijing–Shanghai High-Speed Railway in North China–East China and Beijing–Harbin High-Speed Railway in Northeast China, this study evaluates the development potential of high-speed railway asset energization (Table 1).

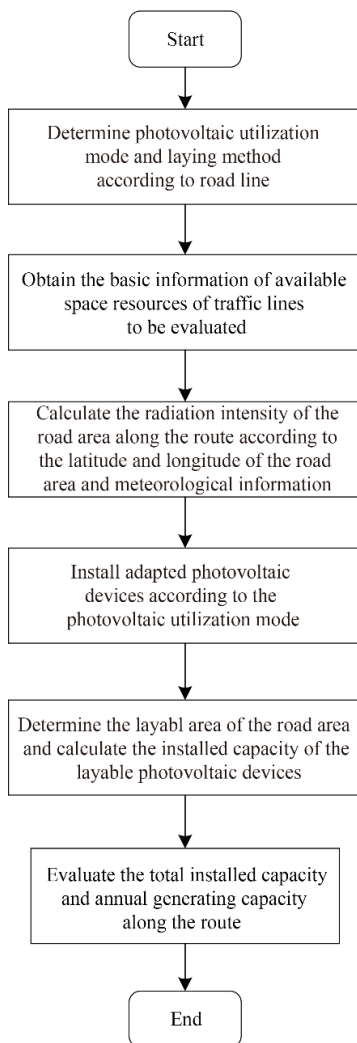


Fig. 2. The model used to assess the exploitable photovoltaic potentials.

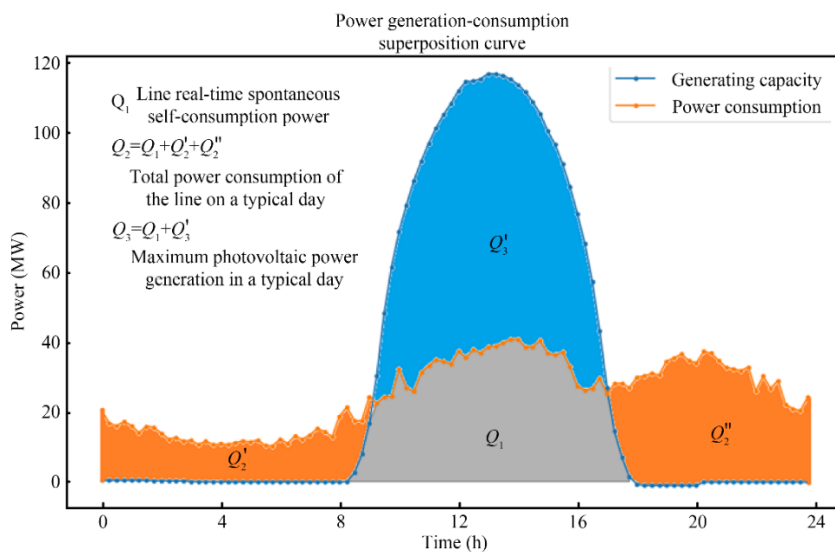


Fig. 3. Energization of transportation infrastructure and power consumption.

Table 1. Calculation of power generation potential of typical land transportation line infrastructure.

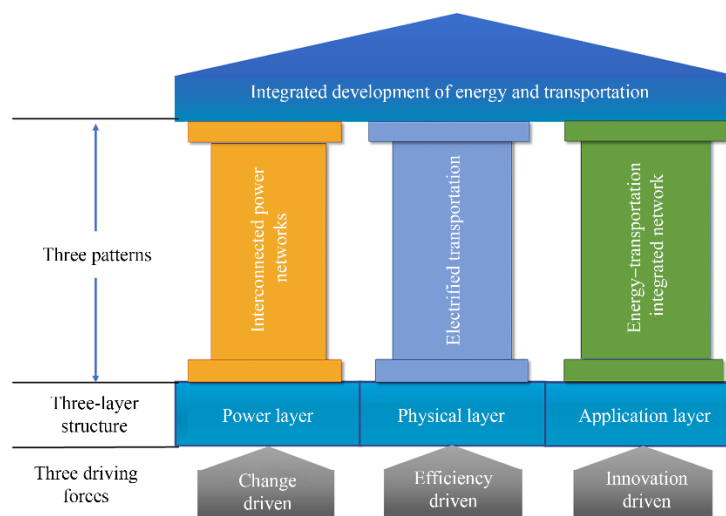
Index	Category	Highway		High-speed railway	
		Beijing– Shanghai	Beijing– Harbin	Beijing– Shanghai	Beijing– Harbin
Available space	Total mileage (km)	1233.4	1209.0	1302.0	1250.0
	Along space ($\times 10^4$ m ²)	511.2	478.3	1065.0	1022.5
	Site space ($\times 10^4$ m ²)	141.1	130.2	144.0	120.9
Generation potential	Installed capacity (10 MW)	27.2	15.1	57.0	54.7
	Annual power generation (GW·h)	471.9	246.4	3177.3	3360.2
	Annual electricity consumption (GW·h)	101.5	85.0	1388.8	1864.1
Evaluation index	Total self-consistency (%)	470.4	295.4	247.8	186.9
	Time self-consistency rate (%)	57.1	56.1	59.1	41.1
	Electrical energy time-shift rate (%)	86.9	77.4	74.0	76.9

To account for the spatial distribution differences of traffic lines in a simplified manner, this study calculates the installed capacity of the Beijing–Shanghai Expressway/Railway and Beijing–Harbin Expressway/Railway using radiation data from 42.5 °N and 35.0 °N, respectively. The findings indicate that the total self-containment rate realized via the photovoltaic energy utilization of transportation infrastructure on highways and high-speed railways exceeds 100%. This implies that the transport system can fully achieve self-containment. The transient self-containment rate falls between 41% and 59%. Hence, the electrical energy generated by the transportation system via asset energization must be stored in an energy storage system or coordinated with the external power grid to meet its energy demands.

5 Development strategy of land transport energy system in China

5.1 Overall strategy

Based on the current situation in China and international trends, in this study, we propose a development strategy for China’s land transportation energy system (Fig. 4). The objective is to foster high-quality and sustainable development in the energy and transportation sectors by constructing a low-carbon and efficient infrastructure system. The land transportation energy system in China can be categorized into three levels: (1) The power layer, which ensures the energy supply for infrastructure operations. Through energy integration at the power layer, the energy structure can be optimized, and the transport industry’s decarbonization competitiveness can be enhanced. (2) The physical layer, encompassing energy and transportation equipment and facilities. This layer plays a central role in improving energy utilization efficiency. By integrating equipment at the physical layer, the development of transportation energy power systems can be clean, low-carbon, and efficient. (3) The application layer, responsible for data information and service functions. This layer facilitates effective connections between energy and transportation social functions through initiatives such as pipe gallery sharing, hub co-construction, and function integration.

**Fig. 4.** Evolution of land transportation and energy integrated systems.

In China, there are three main forms of land transportation energy systems: (1) interconnected power grid, which is primarily driven by the energy industry and utilizes the smart grid as a platform. It provides a reliable and clean energy supply for the transportation system, facilitating the full integration of the power layer within the land transportation energy system. (2) Electrified transport; this form focuses on transportation vehicles within the transportation industry. It involves the electrification transformation and upgrading of transport power sources, leading to the effective integration of physical layer equipment within land transportation energy systems. (3) Energy transportation integration network; this form highlights the significance of energy and transportation networks. Through comprehensive planning, coordinated operations, and maintenance of the land transportation energy system, this network enhances the overall efficiency of the system and realizes deeper integration between the energy and transportation sectors.

These factors have propelled the development of the land transportation energy system in China, driving its evolution, efficiency, and innovation. The energy supply for transportation infrastructure is transitioning from a reliance on distant sources to a combination of distant and nearby sources. This shift is fostering the sustainable development of a re-electrification pattern within the transportation power system, wherein electric energy replaces fossil oil. These proactive changes will bring substantial enhancements to the overall efficiency of the land transportation energy system, leading to the emergence of new technologies and models. The accelerated adoption of clean and low-carbon transportation energy systems is also promoting railway electrification and advancing road transport equipment powered by new energy sources. This collective effort contributes to carbon reduction, energy consumption reduction, quality improvement, and increased efficiency within the transportation and transportation power systems.

5.2 Rail transit energy

Through the transformation and modernization of rail transit energy supply and consumption systems, a comprehensive upgrade will be implemented to realize the clean and re-electrification development of the rail transit energy system. This includes the establishment of a new traction power supply system for electrified railways and a new power system for non-electrified railways, working in synergy to promote the overall cleanliness and electrification of the rail transit energy system.

To maximize the utilization of clean energy, it is crucial to fully leverage the space resources available within rail transit systems and integrate distributed power generation facilities into the electrified rail transit network. This integration enables the development and utilization of natural resources in areas without electrified rail transit. Furthermore, energy and power production equipment will be integrated into the infrastructure of the rail transit system, creating a novel type of infrastructure that possesses energy and transportation attributes. This integration will result in the formation of a non-electrified rail transit system with functions for energy production, conversion, and supply. This system can be regarded as a specific manifestation of the interconnected power grid concept.

In terms of re-electrification, the traction power for non-electrified rail transit has transitioned from fossil fuels to clean electric power. This transition has facilitated the re-electrification of energy within the non-electrified rail transit system through two primary approaches: the use of electric energy as the power source and utilization of hydrogen energy as the locomotive power source, which can be subsequently converted into electric energy through fuel cells. By fully replacing fossil fuel with electric energy in rail transit transportation equipment and employing electric motors as the driving mechanism, energy conversion efficiency surpasses that of internal combustion engines. This achievement leads to enhanced energy conservation and improved efficiency of transportation equipment, ultimately showcasing the direct manifestation of electrified transport.

Considering these foundational elements, we aim to promote a synergistic combination of an interconnected power grid, emphasizing energy production, and electrification, focusing on energy consumption. This approach enables the full utilization of natural resource endowments along rail transit lines, allowing renewable energy generation to supply clean power to rail transit systems. Consequently, a new energy power supply mode emerges, characterized by reliance on both distant and nearby sources. Transporting zero-carbon fuels through the utilization of clean electricity has accelerated the transition from fossil fuels to clean energy sources at transportation terminals. This advancement, in turn, fosters the development of new transportation energy systems that incorporate clean energy generation, zero-carbon raw materials, and electric propulsion.

5.3 Road transportation energy

By exploring the potential for energy utilization in highway transportation assets, we have successfully

established a self-contained energy system for highway infrastructure and new power system for transportation equipment through electrification and hydrogen energy. This achievement marks a significant milestone in realizing a green and intelligent development for the highway transportation energy system.

Regarding the construction of self-contained energy systems for infrastructure, we have divided energy and transportation integration scenarios based on various factors, including China's meteorological, economic, and demographic characteristics, terrain features, distribution of geographical and spatial backbone grids, and traffic load demand distribution. With a comprehensive consideration of factors, such as self-containment rate, penetration rate, economic viability, and carbon emission reduction, priority has been given to regions with favorable natural resources and low energy demand. Based on a cascading approach to develop and utilize the energy potential of transportation infrastructure assets, we aim to establish a self-contained clean energy system for China's highway transportation network.

In terms of electrification and the adoption of hydrogen energy for transportation equipment, we are gradually constructing a self-contained power supply system for road traffic, encompassing a distributed source–grid–load–storage–charging framework. We are also enhancing the integrated service network for hydrogen production, storage, and transportation through the deployment of small-scale green hydrogen production facilities. Additionally, we are conducting research on joint storage and transportation of hydrogen and ammonia to promote a new type of power system for highway transportation equipment that utilizes both hydrogen and ammonia energy. These efforts are crucial in achieving cleaner power for trucks. Based on the development of innovative power equipment and the widespread implementation of charging and hydrogenation service facilities, we can realize the vision of green and intelligent transportation equipment.

6 Innovation directions of land transportation energy system

6.1 Development of complete core equipment

The integration of land transportation and energy relies on a comprehensive set of core equipment for energy capture and transformation, which must possess high reliability and adaptability. The operational scenarios for energy capture, storage, and transformation in land infrastructure vary significantly, often in challenging environments such as extreme cold, desert winds and sand, high-altitude thin air, and corrosive salt fog. Therefore, the integration of transportation infrastructure with energy capture and storage systems faces complex and demanding application environments that impose stringent requirements on equipment stability and reliability.

Renewable energy power generation equipment, including photovoltaic systems, wind turbines, converters, and energy storage systems, exhibit varying performance characteristics and lifecycles depending on the operating environment. This necessitates adaptability in materials, production processes, operational characteristics, and active control functions. The core equipment sets for energy capture and transformation must be designed and adjusted to meet these adaptability requirements.

The transportation sector has been driving the adoption of new energy sources, clean technologies, intelligent systems, digital solutions, lightweight designs, and environmentally friendly practices. This involves the deployment of complete sets of technical equipment, including intelligent high-speed railways, smart roads, automated shipping systems, digital pipelines, intelligent storage and sorting systems, and advanced detection, monitoring, operation, and maintenance technologies for transportation equipment.

6.2 Integration system construction, operation, and maintenance

Scene adaptation is a crucial requirement for the construction, operation, and maintenance of land transportation energy integration systems. It involves optimizing transportation structures and achieving integrated development in the energy sector with a focus on coordination and flexibility. Land transportation energy systems exhibit various modes depending on different scenarios, serving as integrated energy systems and self-contained systems with energy conversion units, transportation infrastructure energy consumption units, and multiple energy storage devices. Efficient and unified energy management systems are essential for their operation.

Energy and transportation systems operate as collaborative planning and operation systems involving both supply and demand participants. Grid access conditions can vary, ranging from strong current to weak current or no power availability. To address these challenges, it is necessary to explore adaptation technologies that facilitate clean energy utilization and improve self-contained capabilities in transportation energy integration systems under strong grid access. Additionally, technologies related to strong active support capacity, stability enhancement of power

electronic equipment when connecting weak grid links, synchronization control, and network construction operations for unique isolated networks in transportation systems and power generation equipment in microgrid systems in remote areas without distribution networks should be developed to meet specific application needs.

6.3 Construction of technical specifications and standards system

The integrated development of energy and transportation is an undeniable trend, and as this integration accelerates, it will lead to significant transformations in industry and technology systems, giving rise to new models and technologies. However, the existing technical specifications and standard systems are insufficient to satisfy the comprehensive demands, technical composition, and industrial landscape of the land transportation energy system. These current specifications and standards only cater to the decentralized fields, failing to meet the technical requirements for renewable energy power generation under adaptive scenarios. Moreover, they lack timeliness and there is a significant gap in supporting the development of new comprehensive fields.

When studying and formulating adaptation standards for land transportation energy systems, it is crucial to maintain a goal-oriented and capability-driven approach. This involves developing a comprehensive plan for relevant technical specifications and standard systems, refining renewable energy standards, and supporting the systematic development of renewable energy sources such as solar, wind, hydrogen, and biomass energy. By considering the interdisciplinary nature of energy and transportation, we can define the scope of standards in the adaptation scenario of land transportation energy systems and establish a technical specification and standard system that encompasses all scenarios. To realize this, it is important to clarify terms and definitions, understand the dynamic characteristics of equipment within the defined scope, and propose corresponding technical requirements for various aspects. These include working environment, power prediction, active/reactive power control, operational adaptability, power quality, start-stop procedures, safety measures, relay protection, off-grid/grid connection control modes, communication and information systems, and detection technologies. By establishing such standards, the development of land transportation energy systems can be guided and regulated, fostering technological innovation and facilitating industrial upgrades.

7 Suggestions

The construction and operation of land transportation energy systems represent innovative projects that transcend industries and sectors. The integration of energy and transportation plays a crucial role in improving resource utilization efficiency and is a pressing requirement for achieving innovative, green, efficient, and coordinated development within the energy and transportation industry under the new development paradigm. Furthermore, it serves as a vital component in realizing carbon peaking and carbon neutrality goals. We are committed to advancing the development of China's land transportation energy system, shifting from a fragmented and uncoordinated development approach to a collaborative model characterized by functional integration and system-wide coordination. This transition will facilitate a deeper integration in terms of form and function, foster efficient collaboration in operational modes, and culminate in the establishment of a clean, efficient, and shared comprehensive infrastructure system.

First, we will steadily promote the development of a modern transportation energy system that places clean energy as the primary energy source and electric energy as the central medium. The global energy revolution has led to a continuous integration of electric energy into the transportation industry. With the support of modern energy technologies, advanced materials, and information and communication technologies, electric energy has gradually replaced fossil fuel consumption in transportation terminals. This significant increase in electrification within the transportation sector has catalyzed the widespread adoption and utilization of clean energy sources.

Second, we aim to develop a novel transportation power system characterized by clean energy generation, low-carbon fuel materials and fuels, and electrification. As we transition away from fossil fuels in transportation terminals, China must leverage its abundant natural resources to establish a low-carbon power supply through renewable energy generation. This will facilitate the provision of zero-carbon fuel materials necessary for advancing transportation electrification. Additionally, we will actively support the innovation of electric transportation equipment.

Third, our objective is to construct new infrastructure that integrates transportation and energy systems. By undertaking comprehensive planning and coordinated development of these two sectors, we aim to merge the attributes of energy and transportation. This entails breaking down industry barriers, establishing mechanisms for integrated design, overall planning, and infrastructure coordination, and optimizing land utilization for transportation and renewable energy purposes. We will actively promote the sharing of transportation routes and the collaborative

construction of transportation hubs. Based on these efforts, we will enhance resource allocation capabilities and establish robust independent guarantees for both energy and transportation sectors.

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