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Integrated Development of Rail Transit and Energies in China: Development Paths and Strategies

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Abstract: Rail transit results in significant energy consumption and high carbon emissions. Transforming the energy structure and developing a novel rail-transit energy system with a self-contained energy supply have become significant approaches to achieving a carbon peak and, eventually, carbon neutrality in China. In this article, we analyze the demand for integrated development of rail transit and energy, summarize the current status and development trends in the integration, and analyze the natural endowments for integration in terms of solar and wind resources. Critical technology paths are proposed based on the characteristics of electrified and non-electrified rail-transit systems, considering the natural endowments of renewable energies. Based on an assessment of the self-contained supply potentials of new energies, a series of scenarios and methods are introduced. A roadmap and suggestions are proposed for developing rail–energy integration to construct a self-contained energy system for rail transit. These suggestions include (1) encouraging technological innovation regarding green and intelligent rail transit to form a technology system for rail–energy integration, (2) implementing major scientific and technological projects to coordinate industrial layouts of new energy and rail transit systems, and (3) formulating support policies to create a policy guarantee system for green financing.

Keywords: rail transit; infrastructure asset energization; natural endowments; self-contained supply; convergent development

1 Introduction

China is rich in renewable energy sources such as wind and solar energy. The rail-transit infrastructure and spaces along the lines have sufficient resources for developing and utilizing such renewable energies. Fully utilizing renewable energies is imperative to building a clean, green, and highly elastic rail-transit energy system, realizing convergent development of rail transit and renewable energies, and promoting a supply and demand revolution in energy and rail transit systems, which have a massive development space. Promoting the convergent development of rail transit and renewable energies helps optimize the energy structure of the transportation system, promotes the development of green, low-carbon, and environmentally friendly transportation systems, and supports China in fulfilling its responsibilities of addressing climate change, national energy security, and improvement of its transportation sector.

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With the goal of new energy utilization in the railway industry, beneficial exploration attempts and application practices have been implemented worldwide. JR-East installed 453-kWp solar panels above the entire platform of the Tokyo Station No. 9 and No. 10 tracks to serve the Tokaido Line 3 trains [1]. Swiss railway operators own six hydropower stations that provide 75% of their traction power needs [2]. A metro operator in Santiago, Chile, built two solar photovoltaic (PV) power plants in 2017 that supplied 60% of the metro's electricity needs, bringing the share of renewable energy to 76% [3]. In the Dutch railway system, wind energy provides 100% of the primary energy [4]. In China, the Beijing South Railway Station began operating a 220-kWp rooftop solar power generation unit in 2008, Wuhan Railway Station built a 2.2-MWp rooftop PV system, and Hangzhou East Station installed a 10-MWp solar power generation device on its canopy and roof [5]. The Xiong'an high-speed railway station laid 42 000 m^2 of PV building materials with a total installed capacity of 6 MW, bringing clean power to the station's service facilities [6]. The Jinan–Qingdao high-speed railway uses idle spaces, such as the station roof and platform canopy along the line, to install PV power generation equipment, resulting in considerable energy conservation and emissions reduction [7].

In theoretical research, scholars have proposed a topology for PV access to rail-transit traction power supply systems [8]. Considering PV access affects the reliability and safety of rail-transit traction power supply systems, it is necessary to build an optimal scheduling and control strategy for the traction power supply system including PV and energy storage [9,10] and establish a planning, sizing, and scheduling optimization model for a new energy microgrid for high-speed rails [11]. Experimental research has shown that hydrogen-driven trains have high technical feasibility in terms of replacing fossil energy in non-electrified railways [12–14]. Energy storage systems have become the focus of the planning and design of railway energy supply systems to suppress the impact of clean energy fluctuations on railway operations [15]. Rail-transit energy storage technology is primarily used for train-braking energy recovery [16]. Research has proposed different solutions for integrating electrified and non-electrified rail transit and clean energy. However, China comprises a vast and complex region; thus, a strategy for convergent development of rail transit and energy based on the natural endowment potentials of China's rail transit is necessary.

Many theoretical methods and technical applications have been developed for utilizing new energy sources in railway operations in China and abroad. The scope of these railway and energy integration applications is small, and the degree of systemization is low, making it difficult to develop a systematic planning and design approach for rail-transit energy integration according to China's national conditions. After reviewing the development history and current status of rail-transit energy integration, the development needs and trends in rail-transit energy integration are comprehensively analyzed, and strategic paths and countermeasures for convergent rail-transit energy development are systematically proposed in this study to provide direction for integrating rail transit and energy systems.

2 Demand analysis of convergent development of rail transit and energy

Safe, efficient, green, low-carbon technologies have become the global consensus for the future development of transportation. As green transportation, railway systems play a prominent role in social and economic development but also face enormous pressure and challenges to reduce emissions and increase efficiency in the context of carbon peaking and carbon neutrality. For a long time, considerable reliance on high-speed railways on external power grids produced high carbon emissions and hidden dangers to social and economic security due to a lack of system flexibility. Mismatches or difficulties in adapting to the spatial layout of the railway network and power grid have caused structural constraints and obstacles to the intelligent, green development of the railway system, especially in areas with weak or no power grids. To comprehensively promote the green, low-carbon transformation of transportation systems, the *14th Five-Year Plan for the Development of a Modern Comprehensive Transportation System* posits that PV power generation and energy storage facilities should be deployed along railway lines to promote the green development of transportation facilities [17]. The railway industry must exploit the potential of renewable energy from its resources and promote the transformation of its energy structure.

The demand for energy security has led to reforms in the energy structure of the rail-transit system. China is rich in natural resources such as wind and light, making it imperative to fully exploit renewable clean energy to build a clean, green, and highly elastic rail-transit energy system, realize green self-consistency with transportation energy, and promote energy and transport system integration. The self-contained energy of the rail-transit system

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can promote optimization and transformation of the energy consumption structure of the rail-transit industry and act as a strategic measure for building transportation power and ensuring the overall safety of national energy.

The demand for green development of rail transit promotes the “cleaning” of primary energy. China and the world are facing severe challenges, including climate change and ecological and environmental pollution, with the transportation industry being the third-largest energy consumer. Utilizing renewable energy with rail-transit infrastructure to provide clean, green primary energy for rail transit can help China achieve its carbon peaking and neutrality goals.

Different natural endowment utilization patterns lead to changes in the forms of rail-transit energy systems. Thus, utilization of the natural endowment of the rail-transit system must comprehensively consider its form and abundance to enable the construction of a power grid for a self-contained energy system suitable for rail transit. Thus, a convergent rail-transit energy development strategy must be formulated to realize and meet the need for constructing self-contained rail-transit energy systems in different geographical regions of the country.

The demand for energy accessibility provides an impetus for transformation to a convergent mode. Intelligent development of the rail-transit system is based on system electrification. Owing to different intensities of power grid construction, some non-electrified railways remain in Central and Western China. A new mode of rail-transit energy integration based on renewable energy must be developed to build an intelligent rail-transit system.

3 Current status and trend of convergent rail-transit and energy development

3.1 Development status

Energy is essential to transportation, and transportation requires significant energy for operation. The convergent development of energy and transportation has always been an important objective for ensuring rational, effective, and sustainable evolution of human society. Every collaborative innovation in energy and transportation has significantly improved social productivity, promoted scientific and technological progress, and shaped the characteristics of human civilization in different periods. The fusion of steam engines and primary fossil energy in coal-powered steam locomotives was the prelude to industrial civilization. The fusion of steam locomotives, railways, and secondary energy and electricity contributed to the second industrial revolution and vigorously promoted the development of industrial civilization. Through previous industrial revolutions, the economic status and strategic patterns of countries worldwide have constantly changed and innovated with the complementary, mutually promoting, and convergent development of energy and transportation [18].

The power systems and infrastructure energy supplies of existing rail-transit equipment are mainly carbon-based-fuel internal combustion engines and electricity. An internal-combustion-engine-driven train uses oil or natural gas as its main power source, converting it into mechanical energy through a transmission device, while an electric train obtains electricity through a traction power supply network or uses stored electric energy to provide power for rail transportation. In terms of infrastructure, rail-transit systems have undergone mechanization and electrification. As rail-transit infrastructure electrification requirements are lower than those for train traction power electrification, rail-transit infrastructure were electrified before the carrying equipment. By the end of 2021, China’s railway electrification rate had reached 73.3%, but the number of diesel locomotives remained at 7800 [19]. In urban rail transit, the popularity of electric locomotives is relatively high; complete electrification of the infrastructure and transportation equipment has been realized. However, many diesel locomotives are used for emergency rescue and interval operations in depots or parking lots.

3.2 Development trend

Future rail-transit energy systems will evolve around the three historical goals of high efficiency, high flexibility, and greening, while rail-transit energy consumption will develop in three innovative directions. First, rail-transit assets will develop in the direction of green energy, mainly in terms of applying new energy supply technologies to the rail-transit system. Second, the energy supply will develop in the direction of self-consistent diversification, mainly through access to new energy outputs, with hybrid energy-storage devices used as intermediate units to provide a diversified energy supply for rail-transit systems. Third, energy management will develop in the direction of synergy and flexibility; through the development of green energy for rail-transit assets and elastic diversification of the energy supply, operations management is gradually developing in the direction of highly collaborative flexibility.

Through transformation to green rail-transit assets, the railway energy system can reduce the external energy supply, mitigate the pressure and burden on the power grid, and improve the efficiency of rail-transit assets.

Promoting a self-consistent energy supply will gradually reduce the contact voltage between the rail-transit energy system and high-voltage power grid, effectively reducing the occurrence of high-voltage discharge hazards such as arcs and coronas in the railway catenary, which is crucial for ensuring safe and stable rail-transit operation. In addition, China's rich renewable transportation resources can be fully utilized through the flexible development of energy management. The full greening of the rail-transit system significantly supports building a greener China and achieving carbon emission reduction goals.

4 Analysis of natural endowment of rail transit and energy integration development

4.1 Solar energy

China is rich in solar energy resources [20]. The total annual solar radiation per square meter is 928–2333 kW·h, with a median value of 1626 kW·h per square meter. The annual average solar energy obtained in China is approximately 1×10^{16} kW·h, equivalent to the energy of 1.2×10^{12} tce. According to latitude, longitude, and climate differences, China can be divided into four types of regions based on solar energy resources [21]. The annual radiation per square meter in a Type I region exceeds 1860 kW·h; Type II region: 1500–1860 kW·h; Type III region: 1200–1500 kW·h; Type IV region: under 1200 kW·h. Table 1 presents the distribution of solar energy resources in China.

Table 1. Regional division of solar energy resources in China.

Resource area	Region
Type I	Ningxia, Qinghai (Haixi), Gansu (Jiayuguan, Wuwei, Zhangye, Jiuquan, Dunhuang, Jinchang), Xinjiang (Hami, Tacheng, Altay, Karamay), Inner Mongolia (except for Chifeng, Tongliao, Xing'an League, Hulunbuir)
Type II	Beijing, Tianjin, Heilongjiang, Jilin, Liaoning, Sichuan, Yunnan, Inner Mongolia (Chifeng, Tongliao, Xing'an League, Hulunbuir), Hebei (Chengde, Zhangjiakou, Tangshan, Qinhuangdao), Shanxi (Datong, Shuozhou, Xinzhou, Yangquan), Shaanxi (Yulin, Yan'an), Qinghai (regions except for Type I), Gansu (regions except for Type I), Xinjiang (regions except for Type I)
Type III	Hebei (regions except for Type II), Shanxi (regions except for Type II), Shaanxi (regions except for Type II), Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Guizhou, Xizang
Type IV	Areas except for Type I, Type II, and Type III resource areas

Note: The division of solar energy resources regions is based on the benchmark on grid electricity price.

Notably, 88.5% of China's rail-transit mileage is located in Type II and Type III light resource regions with significant PV power generation potential. Thus, we can fully utilize these geographical advantages of current rail-transit systems to develop the maximum amount of renewable energy. Implementing distributed new energy power generation using the self-owned space resources of rail transit can improve the comprehensive utilization rate of rail-transit land resources and provide energy for rail transit.

In rail-transit infrastructure, concentrated space resources, such as line sides, station yards, and roofs, have significant potential for developing renewable energy and are a convenient choice for constructing PV power generation systems. As a new and promising method for developing the power potential of rail transit, constructing distributed PV power generation systems in developable rail-transit spaces can help realize the transformation of the rail-transit system from consumer to producer while reducing non-renewable energy power consumption. The resources of rail transit provide a layout space for distributed PV power generation. Rail trains and station loads provide a nearby consumption space for renewable energy to form a new mode of distributed power generation for self-use and reduce purchasing power and carbon emissions of the rail-transit system. A traffic-side power supply using renewable energy and the power grid can use power from the grid when power generation is low and supply power independently of the power grid when power generation is sufficient, producing a traffic-side microgrid.

4.2 Wind energy

China is characterized by its large area, long coastline, monsoon climate, and abundant wind energy resources. According to statistics from the China Meteorological Administration regarding the theoretical value of wind energy resources in China, the national average wind energy density is 100 W/m^2 at a height of 10 m, while the wind energy reserves that can be developed and used on land are 2.53×10^8 kW. If the annual on-grid electricity of onshore wind power is calculated according to the equivalent full load of 2000 h, onshore wind power systems can

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provide approximately 0.5×10^{12} kW·h of electricity per year [22]. China has a rich reserve of exploitable wind energy resources that can become an important part of the future rail-transit energy supply system.

Wind energy changes with time and height. In general, the “three northern regions” of China have significant advantages for developing wind energy systems. Heilongjiang, Jilin, Liaoning, Beijing, Tianjin, Hebei, Henan, Shanxi, Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang are key areas for wind energy development and utilization in China. Inner Mongolia has a flat terrain and high altitude, and the average wind speed at a height of 70 m above the ground can reach 8.0–9.3 m/s, with a power density of 700–1200 W/m^2. Abundant, high-quality, and easily developed wind energy resources have spawned many wind farms. In addition, with cold air in spring and winter and typhoons in summer and autumn, the coastal and island areas in China have formed a 10-km-wide inland extension in Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, Hainan, and other coastal provinces and cities. In areas rich in wind energy resources, the annual available hours are 7000–8000 h. The overall distribution of wind resources in China is presented in Table 2.

Table 2. Regional division of wind energy resources in China.

Resource area	Region
Type I	Inner Mongolia (except for Chifeng, Tongliao, Xing'an League, and Hulunbeir), Xinjiang (Urumqi, Ili Kazak Autonomous Prefecture, Karamay, and Shihezi)
Type II	Hebei (Zhangjiakou, Chengde), Inner Mongolia (Chifeng, Tongliao, Xing'an League, Hulunbuir), Gansu (Jiayuguan, Jiuquan), Yunnan
Type III	Jilin (Baicheng, Songyuan), Heilongjiang (Jixi, Shuangyashan, Qitaihe, Suihua, Yichun, Da Hinggan Mountains), Gansu (except for Jiayuguan and Jiuquan), Xinjiang (except for Urumqi, Ili Kazak Autonomous Prefecture, Karamay, and Shihezi), Ningxia
Type IV	Areas except for Type I, Type II, and Type III resource areas

Note: The division of wind energy resource regions is based on the benchmark on grid electricity price.

5 Technical strategies for convergent development of rail transit and energy

The goals of rail-transit energy integration include changing the energy structure of the rail-transit system through energy self-containment, improving the flexibility of the rail-transit system, and supporting national energy security and carbon-peaking and carbon-neutralization goals. Based on the analysis of the primary energy structure transformation objectives of rail transit, we propose strategies for the convergent development of electrified and non-electrified rail-transit energies.

5.1 Convergent development strategy of electrified rail transit and energy

Convergent development of electrified rail transit and energy involves building a new type of electrified energy supply system via integration of electrified rail transit and renewable energy, with the overall goals being low carbon use, re-electrification, and digitalization. The overall strategy for integrating electrified rail transit and energy includes employing a clean-energy power source and fully utilizing the natural resource endowment of electrified rail transit using advanced power and information technologies.

To achieve convergent development of electrified rail transit and energy, the main considerations are clean transformation of rail-transit energy, energy development of assets, and informatization construction. Using clean energy in rail transit reduces direct and indirect carbon emissions and promotes the low-carbon development of electrified rail-transit systems. In terms of energy assets, fully utilizing existing rail-transit space improves the comprehensive utilization rate and promotes the development of rail-transit electrification. Using advanced information and electronic technologies, an intelligent railway traction power supply system with source–network–storage–vehicle coordination can be built to promote efficient and economical energy use.

5.1.1 Clean energy transformation

Clean energy transformation is important for achieving the goal of low-carbon development of electrified rail transit and energy integration. “Energy cleaning” includes cleaning supply-side production capacity and demand-side energy consumption. The former refers to developing renewable clean energy sources, such as solar and wind energy, as electricity production methods; the latter refers to building a multi-channel clean energy consumption method with efficient resource utilization. By promoting the consumption of clean energy in electrified rail transit, developing electrified rail transit, and reducing diesel locomotive usage, the energy consumption of electrified rail-transit systems can be made clean and green. Clean energy transformation of electrified rail transit is the core goal in achieving green, low-carbon development.

5.1.2 Asset energy development

Energy-based development of electrified rail transit assets is the main path to realizing the re-electrification of rail transit. According to the spatial layout and structural characteristics of electrified rail transit, distributed renewable energy conversion facilities can be built in the laying sections. Using distributed energy facilities, natural resource endowments within the scope of China’s rail transit can be transformed into energy, thus promoting the construction and development of electrified rail transit and building of a new type of electrified rail-transit traction power supply system with clean energy as the main body. Specific approaches include developing land assets along rail-transit lines and developing rail-transit ancillary building assets. Energy-based development of assets is the cornerstone of convergent development of electrified rail transit and energy and re-electrification of rail-transit assets and an important measure for changing the energy supply mode of electrified rail transit.

5.1.3 Informatization construction of electrified rail-transit system

Informatization represents a technical guarantee for efficiently utilizing energy in electrified rail transit and can significantly improve energy reliability and utilization efficiency. Informatization of electrified rail-transit systems can help reach the goal of convergent development of electrified rail transit and energy. Using advanced information and electronic technologies, an intelligent electrified rail-transit power supply system and intelligent system operation management and control platform can be developed. Informatization construction of an electrified rail-transit system is conducted at the local terminal layer and the centralized control layer. At the local terminal layer, the full-cycle state of energy infrastructure can be observed through real-time detection and monitoring of production–storage–distribution facilities. At the centralized control level, the energy efficiency of the entire system can be maximized through collaborative management of multiple energy supply/consumption entities in rail transit (network–source–storage–vehicle).

5.1.4 Application scenario for convergent development of electrified railway and energy

Integrated development of electrified rail transit and energy refers to the adaptive adjustment of new energy power generation equipment suitable for structural integration of electrified rail-transit traction systems, providing clean traction power and realizing adaptive integration and full power consumption. For a split-phase AC traction power supply system, a V/v transformer can be used to construct an additional AC bus or public DC bus of a power regulator. AC and DC microgrids can be constructed to realize near-station access to PV and wind-power generation, respectively, as shown in Figs. 1 and 2.

For the in-phase AC traction power supply system, as the power regulator and electronic power transformer have a common DC side, the DC microgrid can be built using the common DC end to realize near-station access to PV and wind power generation, as shown in Fig. 3.

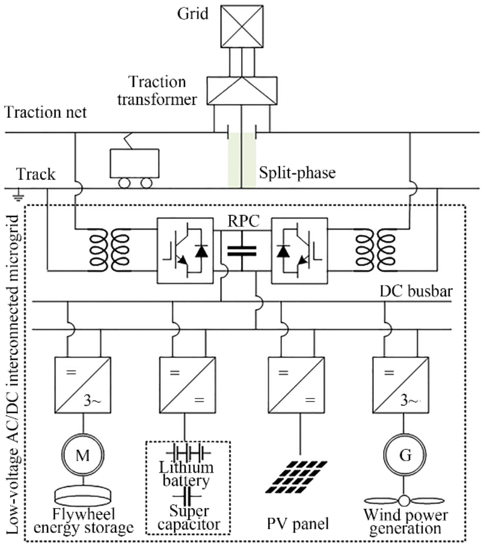

Fig. 1. AC / DC hybrid microgrid connected to two-phase AC rail traction network

Note: G: generator, M: motor; RPC: railway power conditioner.

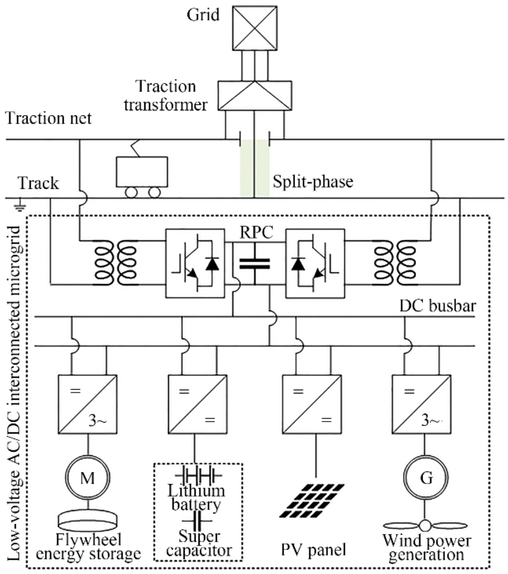

Fig. 2. AC microgrid connected to split-phase AC traction network

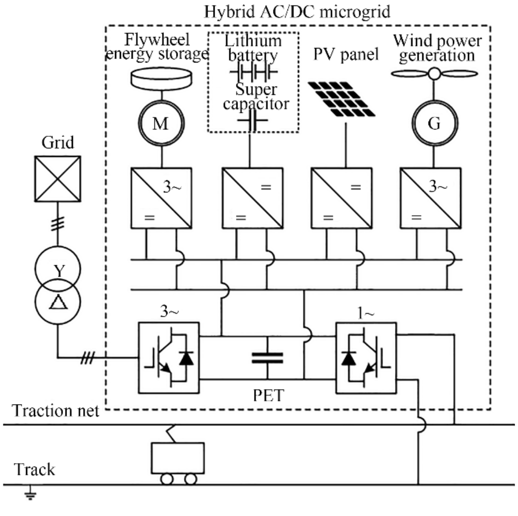

Fig. 3. AC / DC hybrid microgrid connected to in-phase AC rail traction network

Note: Y denotes the star connection method of the transformer, generally expressed in electrical engineering and not in English. PET: power electronic transformer.

Rail-transit carriers should use the space resources on the rail-transit side, fully develop the complementary advantages of multiple controllable resources, maximize development of renewable energy on the rail-transit side, and use the power generation potential of renewable energy to provide a sufficient renewable power supply for the rail-transit energy system. As the largest energy consumer on the rail-transit side, rail-transit carriers can provide sufficient consumption space for renewable energy power generation. After meeting their energy consumption requirements, the remaining energy can be fed back to the power grid. Owing to the volatility of renewable energy power generation and rail-transit carrier power consumption, the energy/power can be shifted in time using energy-storage devices to match the load and power generation. The renewable energy, energy-storage devices, controllable loads, and stable main power supply within a certain geographical range are integrated to form a rail-transit-side microgrid operating in parallel with and independently of the large power grid and isolated islands for high flexibility and high-efficiency operation.

5.2 Convergent development strategy for non-electrified rail transit and energy

Convergent development of non-electrified rail transit and energy is important for promoting comprehensive cleaning and electrification of rail transit. To realize integrated development of non-electrified rail transit and energy, new electrification, and cleanliness, the main approaches are (1) transformation of new power and (2) supply and distribution of new energy. Transformation of new power is the core of the new electrification approach to realizing convergent development of non-electrified rail transit and energy. Supply and distribution of new energy is the primary approach to clean comprehensive development and efficient utilization of natural resource endowments for non-electrified rail transit.

5.2.1 New power transformation

For non-electrified rail transit, power transformation for vehicles is key to constructing new electrified rail transit. By promoting the transformation of the traction power of non-electrified rail transit from fossil fuels to clean electric drives, the traction energy of a non-electrified rail-transit system can be used for new electrification. Clean electric drive methods include drives powered by supercapacitors, power batteries, and hydrogen fuel cells. A hydrogen energy drive uses hydrogen energy as the power source for the train; hydrogen energy is converted into electric energy by fuel cells to drive the train [23]. Using internal combustion-shunting locomotives in electrified rail-transit sections could aid new power transformation. New power transformation of non-electrified rail transit is the primary requirement for green, low-carbon development, electrification of non-electrified rail transit, and internal power for realizing the carbon peak and carbon neutrality goals.

5.2.2 New energy supply and distribution of non-electrified rail transit

For the land-based facilities of a station, the supply and distribution of new energy for non-electrified rail transit is the main path to achieving the goal of a clean and integrated development of non-electrified rail transit and energy. Supply and distribution of new energy includes (1) vigorously promoting the development and utilization of natural resource endowments in the rail-transit area, realizing a self-consistent supply of clean energy, transforming non-electrified rail-transit systems from fossil-energy consumers to clean-energy producers, and (2) building a new non-electrified rail-transit energy supply and distribution system to integrate energy production, conversion, and supply functions. The supply and distribution of new energy is necessary for clean and efficient development of non-electrified rail transit and is a driving force for the realization of the carbon peak and carbon neutrality goals in the field of non-electrified rail transit.

5.2.3 Application scenario for non-electrified rail transit and energy integration

The scenario for convergent development of non-electrified rail transit and energy mainly concerns the electrification and hydrogen energy of vehicles. A special renewable clean energy system is proposed to realize clean energy consumption in non-electrified rail-transit systems and improve the flexibility of railway energy systems. Using renewable energy power generation systems (mainly wind and light) in the near-station areas of rail-transit stations, the system can support energy consumption by non-electrified rail-transit stations and new vehicles through a source–storage–load interaction mode to maintain long-term stable operation.

With the volatility of wind and solar energy and the independent operation modes of new rail-transit vehicles without catenaries, there is a mismatch between a random power supply with climate change and intermittent energy consumption with an operation mode. Thus, a secondary energy system is recommended for non-electrified rail-transit stations as a transitional bridge system between the primary power generation system and the locomotive load. This transitional system consists of electric energy storage, electrochemical energy storage, and charging devices, along with electric hydrogen production, hydrogen storage, and hydrogenation devices, as shown in Fig. 4. The energy produced by the renewable clean energy power generation system is temporarily stored in the secondary energy system. The system is standardized through the energy output configuration (ensuring energy cleanliness).

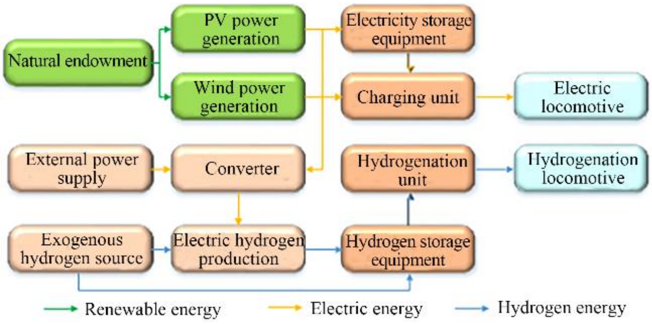

Fig. 4. Renewable clean energy conversion system for non-electrified railways.

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6 Potential calculation and implementation steps for convergent development of rail transit and energy: taking the convergent development of railways and PV systems as an example

Considering railways and photovoltaics as an example, we propose a roadmap for convergent development by measuring the natural endowment potential and energy load of solar energy.

6.1 Calculation of development potential of railway and PV integration in China

The annual average radiation of each region according to a point of similar radiation was used for analysis, presented as follows: Type I region: (30.7°N, 89.85°E), Type II region: (39.4°N, 90.3°E), Type III region: (35.3°N, 114.9°E), and Type IV region: (30.2°N, 108.2°E).

The main types of rail and PV integration are carrier and PV integration, infrastructure and PV integration, and service and PV integration [24–26]. The integration of carriers with PV refers to the placement of PV modules on the tops of train carriages, currently suitable for non-electrified railway rolling stock. The integration of infrastructure with PV refers to the use of space around railway lines for PV modules. Integration of service facilities with PV refers to the use of PV modules on top of stations. The PV output potential for different convergent modes is calculated as [18]

(1) PV output of railway carriers:

$$P_{\mathrm{t}} = n_{\mathrm{t}} \cdot S_{\mathrm{t}} \cdot R_a \cdot \rho \qquad (1)$$

where P_{t} is the PV output of the carrier; n_{t} is the number of coaches; S_{t} is the area of the train roof that can be covered with a PV module; R_a is the national average annual radiation; ρ is the PV module conversion efficiency.

(2) PV output of railway infrastructure:

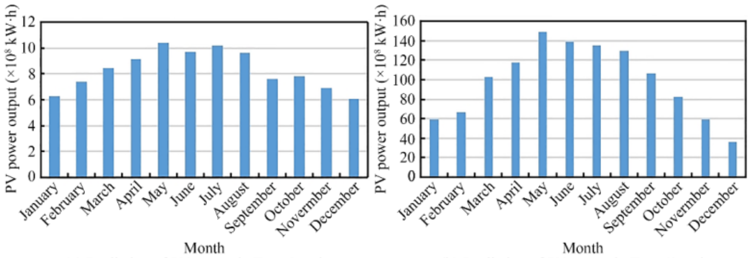
$$P_{\mathrm{r}} = (l_1 \cdot c \cdot R_1 + l_2 \cdot c \cdot R_2 + l_3 \cdot c \cdot R_3 + l_4 \cdot c \cdot R_4) \cdot \rho \qquad (2)$$

where P_{r} is the PV output of the rail line; l_1, l_2, l_3, and l_4 are the lengths of PV lines that can be laid in Type I, Type II, Type III, and Type IV radiation regions, respectively; c is the average PV module width; R_1, R_2, R_3, and R_4 are the average annual radiation levels in each category, respectively.

(3) PV output of railway service facilities:

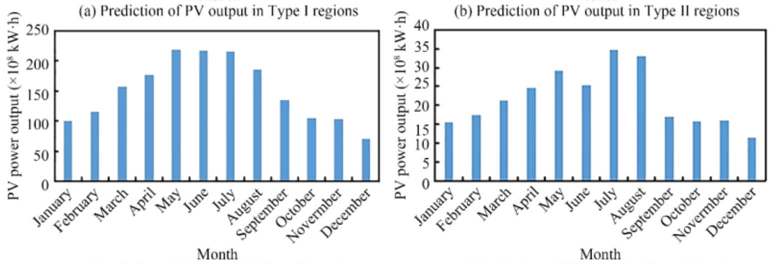
$$P_{\mathrm{s}} = (n_{s1} \cdot R_1 + n_{s2} \cdot R_2 + n_{s3} \cdot R_3 + n_{s4} \cdot R_4) \cdot s_{\mathrm{a}} \cdot \rho \qquad (3)$$

where P_{s} is the PV output of railway service facilities; ns1, n_{s2}, n_{s3}, and n_{s4} are the number of stations in Type I, Type II, Type III, and Type IV radiation areas, respectively, and f is the average station area. According to the solar radiation resources in China, Fig. 5 shows the forecast results for the PV outputs of railways in different regions of China in 2017.



(a) Prediction of PV output in Type I regions

(b) Prediction of PV output in Type II regions



(c) Prediction of PV output in Type III regions

(d) Prediction of PV output in Type IV regions

Fig. 5. Rail-transit (railway) PV output forecast in China (2017) [18].

6.2 Calculation of railway and PV integration potential in the future

6.2.1 Estimation of future PV output potential

Assuming that the growth rate of the number of trains from 2021 to 2025 remains consistent with the size of the railway network and that the space available for trains to lay PV equipment reaches 10% with other conditions remaining unchanged, the annual PV output for rail transport carriers in China could reach 0.11×10^8 k·Wh in 2025, 0.27×10^8 kWh in 2030, and 0.44×10^8 kW·h in 2035.

Assuming consistent growth in the size of the railway network in the four types of light-emitting areas and 10% utilization of the PV space available for laying lines, the annual PV output of China's rail transport infrastructure could reach 4.18×10^{10} kW·h in 2025, 1×10^{11} kW·h in 2030, and 1.66×10^{11} kW·h in 2035.

Assuming that the growth in the number of railway premium stations in the four types of light-emitting areas is consistent with the growth in the scale of railways, with 10% utilization of the PV space available for laying lines at stations with other conditions remaining unchanged, the annual PV output of China's railway premium stations could reach 2.77×10^8 kW·h in 2025, 6.62×10^8 kWh in 2030, and 1.09×10^9 kW·h in 2035.

6.2.2 Energy load forecasting

According to the International Energy Agency [27], China's railway energy demand was 1.57×10^7 tce in 2017 and is expected to be 2.5×10^7 tce by 2030 and 3.29×10^7 tce by 2050. The increased demand for railway electricity in most regions of China can be met by different technologies such as overhead electrification lines; these can also provide a cost-effective means of reducing greenhouse gases and local pollutant emissions. By 2025, it is predicted that China's railway electricity load will reach 1.66×10^7 tce or approximately 1.35×10^{11} kW·h; by 2030, the electricity demand for railway transport in China will reach 2.25×10^7 tce, or approximately 1.83×10^{11} kW·h; by 2035, China's railway electricity load will reach 2.76×10^7 tce or approximately 2.24×10^{11} kW·h [18].

6.3 Roadmap for convergent development of railway energy

Considering the new energy penetration rate as the quantitative index, we present an overall goal and five-year phased-development goals and strategies for railway energy integration from the perspectives of the self-contained electricity rate, energy self-consistency rate, and carbon emission reduction [18]. According to the potential of China's new energy and railway integration over the next 15 years, the new energy penetration rates for China's railway system by 2025, 2030, and 2035 could reach 10%, 20%, and 30%, respectively. According to the railroad PV output and its electricity load demand, the self-contained rates at different times are calculated, and a roadmap for the evolution of new energy integration in railroads from 2021 to 2035 is presented (Fig. 6).

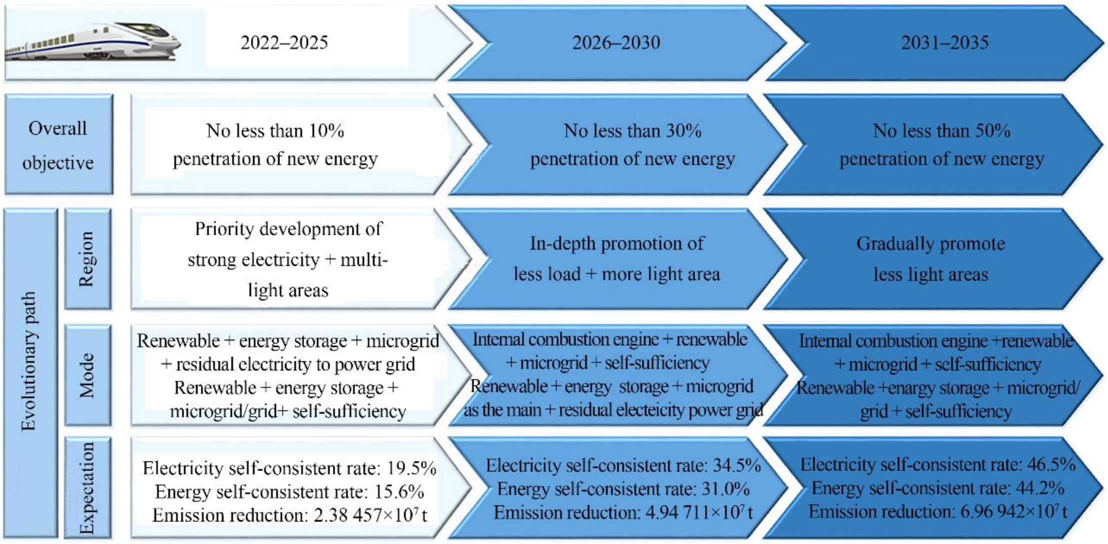


Fig. 6. Roadmap for railway and energy integration.

2022–2025: Priority is given to developing areas with high train operation densities and rich lighting resources, focusing on "renewable energy + energy storage + microgrid + residual power grid" and "renewable energy + energy storage + microgrid/grid + self-sufficiency mode", achieving self-consistency rates of 19.5% and 15.6%, respectively. Combining renewable energy with hybrid energy storage can provide part of the active output; most of the railway energy requirements can be provided by the power grid. The effect of railway energy conservation and emission reduction is significant, and energy efficiency is gradually improved.

2026–2030: Stakeholders should continue to develop areas with high train operation densities and abundant light resources and gradually promote areas with smaller loads and more light, focusing on the modes of "internal

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combustion engine + renewable energy + microgrid + self-sufficiency” and “renewable energy + energy storage + microgrid + residual power grid” achieving self-consistency rates of 34.5% and 31.0%, respectively. The active output provided by renewable energy and hybrid energy storage can be further increased; the residual output can be supplied by the power grid. These considerations could lead to significant progress in railway energy conservation and emissions reduction, and energy efficiency can be further improved, helping to achieve the “carbon peak” goal of the railway.

2031–2035: Stakeholders should continue to develop areas with low train densities and abundant lighting resources and gradually promote the development of other areas and the modes of “internal combustion engine + renewable energy + microgrid + self-sufficiency” and “renewable energy + energy storage + microgrid/grid + self-sufficiency”, achieving self-consistency rates of 46.5% and 44.2%, respectively. Renewable energy and hybrid energy storage can provide almost half of the active output; the remaining output can be supplied by the power grid. This level of intelligent, green, efficient, and environment-friendly railway transportation can be significantly improved, moving toward the goal of “carbon neutrality.”

7 Suggestions

7.1 Encouraging green, intelligent rail transportation technology innovation and building rail transportation energy integration technology systems

Research and development of new energy rail-transportation carrier technologies should be strengthened, aiming to achieve breakthroughs in high-performance electric, hydrogen energy-driven, and low-carbon energy-driven vehicle equipment technologies, rail-transit hybrid vehicle equipment technology, and non-carbon-based energy technology. Further research and development is recommended for self-contained rail-transit energy systems and multi-energy transformation and regulation of these systems for high efficiency and elasticity. Digitization, intelligence, and integration of rail-transit technologies should be researched to build a green and smart rail-transit system.

7.2 Implementing core scientific and technological research plan and coordinating layout of new energy and rail-transit industries

Strengthening the guidance of the national science and technology action strategy, formulating a scientific and technological development plan and a development map for rail-transit energy integration, and deploying key scientific and technological research plans in the field are recommended. The focus should be a self-consistent rail-transit energy system, coordination of the layouts of national laboratories, key laboratories, and technological innovation centers, cultivation and development of innovative enterprises, and building an innovative consortium for rail-transit energy integration. These considerations should produce breakthroughs in the design, standards, and implementation of self-consistent rail-transit energy systems. Further recommendations include accelerating research and development, demonstration, and large-scale application of rail-transit energy integration technologies and building a government–industry–education–research–application technology system deeply integrated with new power systems constructions. Stakeholders should continue to strengthen support for self-contained rail-transit energy technology research, development, and demonstration projects and promote high-quality sustainable development of the rail-transit and energy industries.

7.3 Developing policies to lead convergent development of rail transit and energy and establishing a green financial policy guarantee system

Resource allocation and market-oriented means should be used to reduce rail-transit energy construction costs, with plenty of opportunities present for electricity market reform and carbon emission trading mechanisms [28]. The resource-allocation potential of the rail-transit energy system as coordinated by source–network–vehicle–storage can be developed, optimization of the rail-transit energy structure can be promoted, and investment income for rail-transit energy integration can be increased. In addition, it is recommended to strengthen government leadership, formulate cooperation policies between the energy and power sector and rail-transit industry, optimize investment, financing, and tax policies for the rail-transit energy industry, and improve the overall planning, system integration design, and infrastructure construction mechanisms for rail transit and new energy land use to promote the realization of the carbon-peaking and carbon-neutrality goals in the transportation industry.

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