INTEGRATED DEVELOPMENT OF RAIL TRANSIT AND NEW ENERGY

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Abstract

Rail transit is recognized as a significant sector in terms of energy consumption and carbon emissions. The transformation of its energy structure and the establishment of a new rail transit energy system characterized by energy self-sufficiency are considered crucial measures for achieving the "dual-carbon" goals. A systematic investigation of the integrated development of rail transit and new energy is conducted in this paper. Against the backdrop of global climate change and energy transition, the demand characteristics for such integration are analyzed, and the corresponding forms and models are categorized. Furthermore, key enabling technologies for the integrated development of rail transit and new energy are explored, with directional guidance for future advancements in this field being provided.

1 Introduction

Unprecedented energy and environmental challenges are currently being faced by the world. With global industrialization and urbanization being accelerated, a continuous rise in energy demand is observed, while severe environmental pollution and climate change issues have been caused by the extensive use of traditional fossil fuels [1]. Against this backdrop, clean energy development and energy structure transition have been recognized as a global consensus. Meanwhile, the transportation sector, being identified as one of the primary sources of energy consumption and carbon emissions, is considered to play a crucial role in the achievement of global sustainable development goals through green and low-carbon transformation [2].

Rail transit is widely regarded as one of the most sustainable transportation modes due to its high efficiency, safety, and large capacity [3]. However, high energy consumption and inefficiency are still exhibited by traditional rail transit systems. In non-electrified sections, not only is energy inefficiency demonstrated by diesel locomotives, but significant pollutant emissions are also generated [4, 5]. Even in electrified sections, if coal-fired power generation is predominantly relied upon for electricity supply, the indirect carbon emissions remain non-negligible. Moreover, high carbon emissions are not only sustained by the long-term heavy dependence of rail transit on external power grids, but substantial risks to socioeconomic stability are also posed due to a lack of system resilience [6, 7]. Structural constraints and bottlenecks on the intelligent and green development of rail transit operations, maintenance, and services are imposed by the spatial mismatch or incompatibility between rail transit networks and power grids—particularly in regions where grid infrastructure is weak or non-existent [8].

Abundant renewable energy resources such as wind and solar power are endowed in China, while ample opportunities for renewable energy utilization are provided by rail transit infrastructure and its surrounding spaces [9. 10]. Under the guidance of the "dual-carbon" goals, the integrated development of rail transit and new energy has been promoted. Through the effective combination of renewable energy technologies (such as solar, wind, and hydrogen) with rail transit systems, energy efficiency can be significantly improved, carbon emissions can be reduced, and economic, social, and environmental benefits can be achieved [11, 12]. Therefore, great significance is attached to the promotion of the integrated development of rail transit and new energy in realizing carbon peak and neutrality targets in the transportation sector and establishing a clean, low-carbon, safe, and efficient energy system.

The characteristics and demands of the integrated development of rail transit and new energy are comprehensively analyzed in this paper, its forms and models are systematically categorized, and an in-depth study on its foundational requirements and technological pathways is conducted. Significant contributions to the fostering of innovation and progress in this field are expected to be made through these efforts.

2. Analysis of Demand for Integrated Development of Rail Transit and New Energy

2.1 Background of global climate change and energy transition

One of the most severe challenges facing humanity was recognized to be global climate change. An approximate rise of 1.1℃ in global average temperature compared to pre-industrial levels was reported by the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, with a continuing increase rate of 0.2℃ per decade being observed. A series of environmental issues, including frequent extreme weather events, rising sea levels, and biodiversity loss, were caused by climate change, with significant threats to the sustainable development of human society being posed. Approximately 75% of global greenhouse gas emissions were accounted for by energy-related carbon dioxide emissions, as was indicated by data from the International Energy Agency, with about 24% of energy-related carbon dioxide emissions being contributed by the transportation sector. Within the transportation sector, around 8% of global passenger traffic and 7% of freight traffic were carried by rail transport, while only about 2% of the sector's energy consumption and 0.5% of carbon dioxide emissions were accounted for by it. From these findings, rail transit was demonstrated to be a relatively environmentally friendly mode of transportation, though potential and opportunity for further emission reductions were shown to remain.

2.2 Characteristics of rail transit energy consumption

The energy consumption of rail transit exhibits the following characteristics:

- Predominantly electric propulsion: Modern rail transit systems are primarily powered by electric propulsion, with electrification rates being continuously increased. For instance, in China, an increase in the railway electrification rate from 46.6% in 2010 to 72.8% in 2022 was observed. The energy consumption of electrified rail transit is mainly manifested as electricity demand, which enables the integration of renewable energy sources to be facilitated.
- High energy efficiency: According to IEA data, the energy intensity (energy consumption per passenger-kilometer) of rail passenger transport is shown to be approximately 1/8 that of aviation and 1/4 that of private cars. Similarly, the energy intensity of rail freight transport (energy consumption per ton-kilometre) is calculated to be about 1/5 that of road freight and 1/40 that of air freight.
- Significant load fluctuations: High-power traction is required during train acceleration, while energy recovery can be achieved during braking phases [13]. Opportunities for optimized energy management and energy storage system applications are created by such load variability.
- Wide spatial distribution: Extensive networks with numerous stations are featured by rail transit systems, leading to energy consumption points being geographically dispersed. Favourable conditions for the implementation of distributed energy systems are provided by this characteristic.
- Abundant infrastructure assets: Substantial infrastructure is possessed by rail transit, including stations, depots, and right-of-way corridors, which can be utilized for new energy development. Rooftop photovoltaic systems and wind power installations along rail lines are included as examples of such development [14, 15].

In Tab. 1, it presents a comparative analysis of energy consumption characteristics across different types of rail transit systems.

Table 1. Characteristics of energy consumption in comparable rail transit

Types of Rail Transportation	Major Energy Types	Electrification rate	Energy consumption characteristics
High-speed Railway	Electricity	100%	High speed, high power, high energy efficiency
Ordinary Railway	Electricity, Diesel	40-80%	Medium speed, medium power, low energy efficiency
Urban rail connection	Electricity	100%	Low speed, frequent start-stop, regenerative braking energy recovery

2.3 Demand analysis

A critical role in urban sustainable development is played by rail transit as the backbone of urban public transportation systems, which is attributed to its safety, reliability, and environmental performance. With the establishment of the "dual-carbon" goals and the rapid advancement of new energy technologies, unprecedented opportunities for greening, intelligentization, and efficiency enhancement of rail transit systems have been created. The imperative for integrating rail transit with new energy is systematically examined in this section from four dimensions: policy compliance, economic optimization, green development, and system resilience.

Fig. 1 Thinking needs for the integration of rail transit and new energy development

2.3.1 Policy compliance: The transformation of energy structures in rail transit is being compelled by global carbon neutrality commitments. Following the official announcement of China's "carbon peak by 2030 and carbon neutrality by 2060" targets in 2020, energy conservation, emission reduction, and new energy applications in the transportation sector were explicitly emphasized in subsequent policy documents, including the 14th Five-Year Plan for Modern Integrated Transportation System Development* and Urban Rail Transit Planning, Construction and Operation Management Standards. Specific requirements for transportation electrification and energy structure optimization were established internationally by the European Green Deal and the U.S. Clean Power Plan, with the coordinated utilization of rail transit systems with wind, solar, biomass and other renewable energy sources being accelerated. Strategic guidance is provided by these policy drivers, while substantial support is also offered through market mechanisms such as fiscal subsidies, tax incentives, and carbon emission trading schemes.

2.3.2 Economic Optimization: From an economic perspective, it is indicated by data from the Comprehensive Transportation Research Institute of China's National

Development and Reform Commission that in 2023, an average operational cost of 34.3 RMB per vehicle-kilometre was reached by urban rail transit systems nationwide, with the primary expenditure component being constituted by electricity costs. A proportion of 20%-40% of total operational costs is accounted for by electricity expenses, reaching up to 50% for lines where higher energy consumption is exhibited. Dependence on conventional power grids can be effectively reduced through the integration of new energy, while peak load pressures are alleviated and electricity price volatility risks are mitigated. Meanwhile, distributed energy solutions such as photovoltaic facades and rooftop solar power generation can be implemented by rail transit systems, with synergistic "generation-grid-load" effects being created. Reduced energy costs per passenger-kilometre can be achieved by new energy-integrated rail transit systems, as is demonstrated by Life-Cycle Cost Analysis (LCCA). This economic optimization can be modeled as:

$$LCC = C_{cap} + \sum_{t=1}^{T} \frac{C_{op}(t)}{(1+r)^t} \tag{1}$$

where C_{cap} represent initial investment costs, C_{op} denote annual operational costs in year t, r indicate the discount rate. Through new energy integration, the energy procurement cost component $C_{op}(t)$ decreases, thereby optimizing the overall Life-Cycle Cost (LCC).

2.3.3 Green Development: The transition of urban transportation toward low-carbon and zero-carbon solutions is necessitated by the development philosophy that "lucid waters and lush mountains are invaluable assets". While green characteristics such as high capacity and low accident rates are inherently possessed by rail transit, substantial electricity consumption is still required for its operation. Genuine carbon emission reduction cannot be achieved if the power generation mix is dominated by fossil fuels. Not only can the carbon emission intensity of rail transit systems be significantly reduced through the integration of renewable energy sources such as wind and solar power, but peak shaving and valley filling can also be enabled through energy storage systems, thereby resulting in further enhancement of energy utilization efficiency. Specifically, the discharge of stored renewable energy can be implemented during daytime peak periods, while charging is conducted during night time or off-peak hours, with optimal load balancing being achieved.

2.3.4 System Resilience: Exceptionally high standards of safety and operational continuity are demanded by urban rail transit systems, as large-scale passenger stranding and significant social impacts may be caused by any power interruption [16]. "Single-point failure" risks are introduced by traditional reliance on a single power grid, while continuous operation cannot be ensured during extreme weather events, natural disasters, or grid failures. A "multi-source, multi-point, microgrid" architecture can be established through the integration of diversified renewable energy sources coupled with appropriately sized energy storage, with system resilience being substantially improved. A typical microgrid switching mode can be described as follows:

$$P_{\mathrm{s}}(t) = \sum_{i=1}^{N} P_{\mathrm{ne},i}(t) + P_{\mathrm{es}}(t) + P_{\mathrm{g}}(t) \tag{2}$$

Where $P_{\mathrm{ne},i}$ represent the power output of the *i*-th renewable energy source, $P_{\mathrm{es},i}$ denotes the energy storage output, P_{g} indicates power supply from the public grid. Continuous power supply to critical equipment and signaling systems can be maintained by the system during grid failures or renewable energy fluctuations through autonomous regulation performed by energy storage systems and micro grids.

In summary, strategic objectives and policy support are provided through policy-driven mechanisms; substantial operational cost benefits are achieved via economic optimization; alignment with national "dual-carbon" targets is realized through green development initiatives, with significant reductions in rail transit carbon emissions being obtained; while safe and reliable operation under extreme conditions is ensured through system resilience enhancement. The integrated development of rail transit and new energy systems is collectively driven by these four fundamental imperatives, with a robust foundation for subsequent technological strategies and engineering implementations being established.

3 Configuration Modes for Rail Transit-New Energy Integration

Under the decarbonization-oriented paradigm, a mutually reinforcing relationship is established between rail transit and new energy systems: energy serves as the fundamental basis for transportation systems, while rail transit functions as a primary energy consumption vector. Through continuous interaction and co-evolution, four distinct integration modes with differentiated dominant characteristics are emerging in Fig. 2.

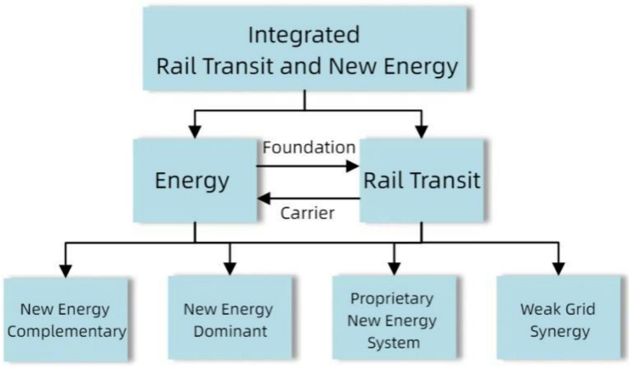

Fig. 2 Integration model

3.1 New energy complementary rail transit systems

New energy complementary rail transit systems are primarily implemented in urban rail networks and electrified trunk lines where limited available rooftop or open spaces along the routes constrain the installation capacity of local photovoltaic and wind power generation to meet traction power demands.

In this configuration, the traction power supply system remains predominantly supported by the existing robust grid infrastructure, with renewable generation serving as auxiliary power that is fed into the traction network through grid-connection. Operationally, the main substation receives power from the national grid, with train traction loads being jointly supported by a "grid-dominant, renewable-supplemental" mechanism. Meanwhile, electricity generated from photovoltaic and wind sources is prioritized for on-site consumption, with surplus energy being fed back into the grid following a "self-generation with residual grid feed-in" strategy, thereby achieving optimal energy allocation and utilization. The energy exchange pathways are illustrated in Fig. 3.

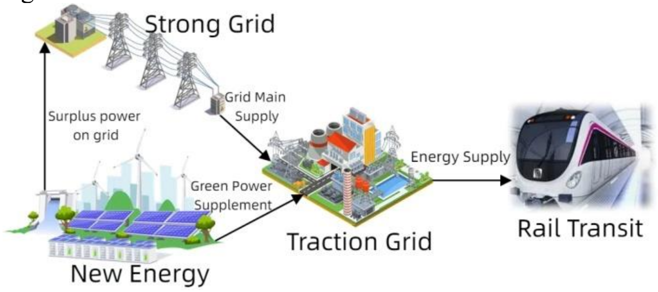

Fig. 3 New Energy Complementary Energy Interaction Path

3.2 New energy dominant rail transit systems

For non-electrified trunk lines in grid-weak or off-grid areas, new energy dominant rail transit systems can be established based on abundant land and renewable resources (wind, solar, and hydro), featuring independent "renewable energy plus energy storage" traction power supply system's isolated from regional grids. In system design, wind, photovoltaic, hydroelectric, or hydrogen production units are configured as primary generation components, complemented by energy storage devices that maintain stable output through "peak-shifting and load-levelling" temporal regulation, with bidirectional energy exchange capability enabled through traction energy absorption when required.

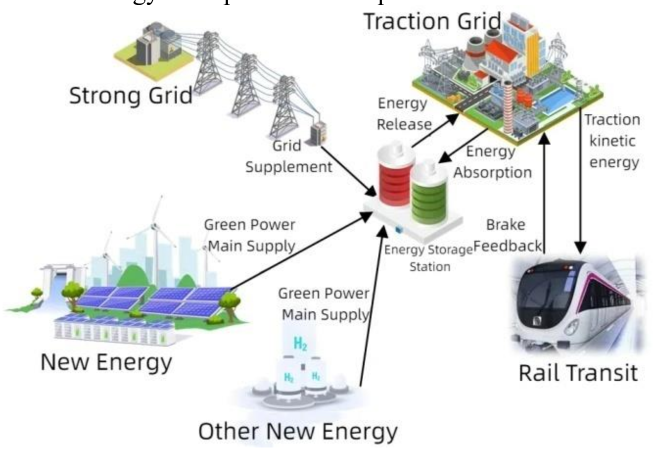

Fig. 4 New Energy Dominant Energy Interaction Path

During operation, an energy coordination strategy of "new energy dominant, distribution grid-supplemented, storage-core, and traction feedback" is implemented to ensure continuous and reliable traction power supply. The energy storage system achieves load balancing through "temporal aggregation and concentrated discharge" among power sources. The complete energy flow pathway is detailed in Figure 4.

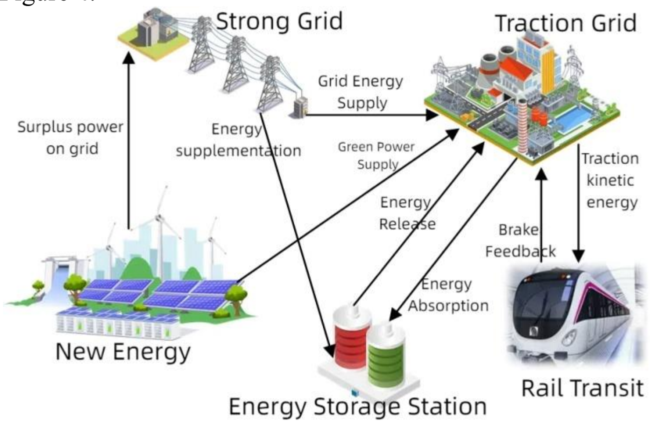

Fig. 5 Proprietary New Energy System Energy Interaction Path

3.3 Proprietary new energy rail transit systems

In electrified trunk railway corridors with robust grid infrastructure, large-scale photovoltaic and wind power installations can be deployed to enable reverse power flow to the grid, thereby establishing the traction network's "generation" attribute. Concurrently, high-capacity energy storage stations constructed along the route provide grid ancillary services including frequency regulation and reactive power compensation, demonstrating the traction network's "storage" functionality. This operational paradigm is established within a "strong-grid-primary, renewable-priority, and storage-auxiliary" framework: renewable generation is preferentially allocated to train traction loads, with surplus energy distributed according to a "self-consumption-first then grid feed-in" principle. The energy storage stations perform dual functions by absorbing regenerative braking energy from trains while simultaneously responding to grid ancillary service requests, enabling bidirectional energy flows. The system not only enhances energy utilization efficiency but also improves operational economics through multiple revenue streams from renewable generation and energy storage services. The energy exchange pathways of pproprietary new energy rail transit systems are illustrated in Figure 5.

3.4 Weak grid coordinated proprietary new energy rail transit systems

For railway lines located at grid extremities with insufficient network support capacity and significant load fluctuations, an integrated "generation-storage-grid" coordinated control scheme can be implemented through deep coupling of distributed renewable resources and energy storage facilities along the corridor. In this operational mode, the traction power supply system is fundamentally structured on a "weak grid plus energy storage" framework, where renewable generation is prioritized for immediate consumption. When renewable power proves inadequate, the energy storage units and weak grid jointly provide supplementary power. During periods of generation surplus, power fluctuations are mitigated through energy storage systems, with regenerative braking energy being stored in either onboard or wayside storage devices. This configuration employs a "renewable-storage coordination with weak-grid supplementation" strategy to effectively balance dynamic power variations and ensure stable traction system operation. The energy exchange pathways of weak grid coordinated dedicated renewable energy systems are systematically illustrated in Figure 6.

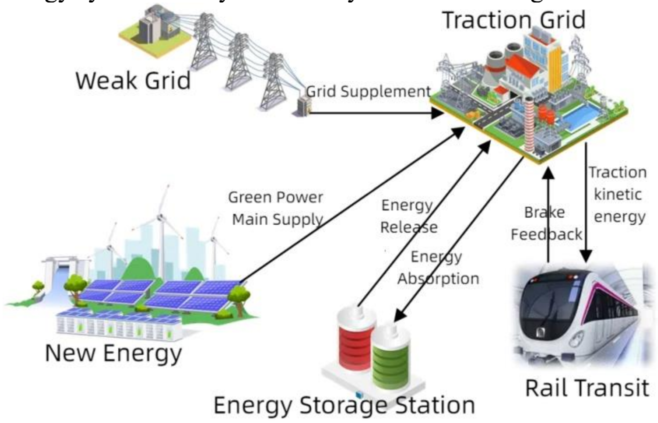

Fig. 6 Weak Grid Coordinated Proprietary New Energy System Energy Interaction Path

The aforementioned four operational modes have been systematically designed to address practical requirements under varying grid conditions and resource endowments, establishing diversified sustainable development pathways for rail transit systems ranging from "grid-dominant supplementation" and "renewable self-sufficiency" to "energy feedback to grid" and "weak-grid resilience". Distinct operational mechanisms and energy flow patterns are emphasized in each configuration, with their complementary characteristics providing comprehensive solutions for achieving both green transformation of rail transit systems and synergistic optimization with energy systems.

4 Suggestions for Integration Development of Rail Transit-Energy

The coordinated development of rail transit and new energy remains in its nascent stage, where a suite of critical technologies is urgently required to be implemented—including digital information and communication technologies, power electronic conversion and control technologies, new energy micro-grid cluster control technologies, and high-performance energy storage technologies. These technologies are expected to facilitate innovative equipment and operational modes for integrated systems, while enhancing planning configuration efficiency, system performance, operational resilience, energy dispatch accuracy, and protection control capabilities. Consequently, a comprehensive closed-loop technological theory and engineering framework can be established.

4.1 Digital information and communication technologies

The efficient operation of integrated systems must be supported by digital technologies including IoT, big data, cloud computing and artificial intelligence to achieve end-to-end data acquisition, transmission, storage and intelligent analysis from device level to regional/system level. Through predictive diagnosis and visualization platforms, critical equipment and operational status can be continuously monitored in real-time, with potential failures being preemptively identified. Dynamic adaptive algorithms are employed to perform online regulation of traction power supply and renewable energy output, ensuring system safety, stability and flexible response under variable operating conditions.

4.2 Power electronic conversion and control technologies

The diversified requirements of urban rail, electrified trunk sections, and non-electrified segments are addressed through seamless coupling of various generation units (wind turbines, photovoltaic systems, hydrogen/gas turbines, and small hydropower plants), distribution networks (10 kV/35 kV), and energy storage devices, which is achieved by power electronic converters. Multiple operational modes, including grid-connected coordination, independent off-grid operation, emergency power support, ancillary services provision, and primary/secondary frequency and voltage regulation, are supported through refined device-level and system-level control strategies. High-degree self-organization capability, adaptive operational performance, and optimal operation selection are enabled, resulting in significant enhancements in overall system resilience and operational efficiency being obtained.

4.3 Renewable energy micro-grid cluster control technology

The integration of demand-oriented distributed renewable energy and energy storage resources along rail corridors enables the formation of wide-area "micro-grid clusters" characterized by electrical interconnection, energy interaction and mutual power supply protection. Through the synergistic combination of global optimal dispatch and local autonomous control, coordinated operation among multiple micro grids can be achieved across spatiotemporal scales, with flexible power supply mode switching capability being realized to simultaneously enhance energy supply reliability and improve system resilience against renewable generation fluctuations and external disturbances.

4.4 High-Performance energy storage technologies

Energy storage devices, functioning as the energy buffering and distribution hubs in integrated systems, must be endowed with large capacity, high-rate capability, low cost, enhanced safety, and prolonged cycle life to address the stochastic nature of renewable energy generation and the impulsive characteristics of train traction loads. Through the implementation of a "time-phased energy aggregation and rapid discharge" mechanism, advanced electrochemical, battery-based, or physical energy storage systems can be utilized to achieve real-time power discrepancy mitigation between traction demands and renewable energy supply, ensure autonomous energy dispatch, and significantly enhance both dynamic stability and energy efficiency levels in rail transit-energy integrated systems.

5 Conclusions

The crucial pathway for achieving carbon peak and neutrality targets in the transportation sector, along with the establishment of a clean, low-carbon, safe and efficient energy system, has been demonstrated to be the integrated development of rail transit and new energy. The background, demand characteristics, technical features and implementation approaches of rail transit-new energy integration are systematically investigated in this study. Significant benefits in terms of energy conservation, environmental protection, economic returns and social value creation are indicated by the research findings to be realizable through such integrated development. Broader implementation prospects are expected to be achieved with anticipated technological advancements and policy support. Accelerated progress is recommended to be made through coordinated efforts in three key dimensions: technological innovation, industrial deployment, and policy safeguards, whereby substantial support for both dual-carbon goal realization and transportation power nation building is provided.

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