Research on Key Technologies and Development Trends of Expressway Traffic and Energy Integration

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Abstract. Currently, research on the key technologies and development trends of expressway traffic and energy integration is insufficient. This paper, through the "Research and Engineering Demonstration of Key Technologies for Comprehensive Traffic and Energy Integration" major scientific and technological project, aims to establish a technological system for expressway traffic and energy integration, mastering the critical technologies of this integration, forming comprehensive solutions for expressway traffic-energy integration, and proposing suggestions for the development layout of this integration. The paper focuses on the study of key technologies for traffic and energy integration in the expressway sector, combining the process of achieving the anticipated goals with their intrinsic relationships. This research fills the gap in multi-level integrated fusion systems and demonstration applications in the domestic traffic and energy fields, playing a significant demonstrative role in China's overall strategy for low-carbon transformation in the typical transportation industry and leading the development of the traffic-energy integration industry.

Keywords: Transportation Engineering; Traffic-Energy Integration; Photovoltaic Slope; Service Area.

1 Introduction

Since the 21st century, both the energy and transportation sectors have seen rapid development, leading to profound changes in their structures. They have achieved integrated convergence in terms of structure and efficient synergy in function, collectively displaying a trend towards extensive interconnectivity, green low-carbon development, and economic efficiency. The interrelationship between these two sectors is deepening, and their converging developmental characteristics are becoming increasingly evident[1].

Firstly, the supply and demand characteristics of energy and transportation have evolved. Both sectors in China have transitioned from a phase of rapid growth to one of high-quality development. There is robust growth in demand for transportation energy, with the rapid development of interactive energy facilities like distributed energy and energy storage. New forms of energy, such as multi-energy supply, comprehensive services, and intelligent energy usage, are constantly emerging, setting new require-

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ments and creating unprecedented opportunities for the energy utilization of transportation assets. Secondly, new challenges have arisen for the safe operation of energy and transportation systems. The large-scale development of renewable energy and its high proportion of integration into the grid, combined with new risk factors like cybersecurity and traditional issues like natural disasters and external damage, are placing unprecedented pressure and challenges on the overall safe operation of energy networks, particularly within transportation systems. To address these developmental challenges, the integration of energy and transportation (referred to as traffic-energy integration) must be guided by national circumstances and actual needs. This involves implementing various reform measures, accelerating the construction of an integrated transportation-energy development system, further enriching the integration models between the transportation system and energy systems (especially renewable energy), and significantly enhancing the energy self-sufficiency of transportation systems[2].

In the face of severe challenges posed by resource scarcity, climate change, and environmental pollution, driving a revolution in transportation and energy supply and promoting industrial transformation and upgrading is the fundamental approach to addressing these challenges. Under the global trend of energy transitioning towards cleanliness and transportation towards greenness, the energy system is shifting from fossil fuel dominance to clean energy leadership. Simultaneously, the revolution in transportation energy towards cleanliness and power electrification continues to advance. The ongoing development of energy utilization in transportation infrastructure and the electrification of vehicles can not only achieve clean substitution on the energy supply side and electrical substitution on the transportation power side but also promote higher quality and more sustainable development in both the energy and transportation sectors. Accelerating the technological and institutional revolutions in these fields, optimizing their systems, and achieving independent innovation can inject new driving forces into China's economic and social development. The integrated strategic planning and development of energy and transportation systems are the inevitable trends for achieving their sustainable development[3].

2 Research on the Technical System of Expressway Traffic-Energy Integration

2.1 Research on Expressway Technical Architecture and Typical Application Scenarios

2.1.1 Conceptual Connotation and Development Characteristics of Traffic-Energy Integration.

(1)Conceptual Connotation of Traffic-Energy Integration

Energy serves as the fundamental power source ensuring the normal operation of transportation systems, while transportation is the critical lifeline supporting the distribution and transportation of energy resources. Promoting the integrated development of traffic and energy is conducive to unlocking the potential for clean energy development within transportation infrastructure, advancing clean energy substitution and low-carbon transformation in transportation, and enhancing the significant energy storage and regulation functions that new transportation networks can provide to new energy systems. This integration is of great significance for deepening the support and coordination between transportation and energy networks and for the joint realization of carbon peak and carbon neutrality.

(2)Development Characteristics of Traffic-Energy Integration

The future development of traffic and energy integration will reflect important characteristics such as green and low-carbon, safety and reliability, intelligence and flexibility, and economic efficiency.

Green and Low-Carbon. The transportation industry not only needs to utilize new and clean energy sources but also acts as a key supplier of clean energy. It aims to gradually achieve near-zero emissions of greenhouse gases and pollutants throughout the industry's entire lifecycle, thereby establishing a green and low-carbon transportation system.

Safety and Reliability. Through an integrated energy production, supply, and sales system that incorporates source-grid-load-storage and multi-source complementarity, the reliable energy supply needs of transportation infrastructure and vehicles can be ensured. The system also relies on diversified modes of transportation to guarantee efficient and smooth energy transportation under various conditions.

Intelligence and Flexibility. By fully applying information technology and intelligent systems, the transportation industry can achieve smart, flexible, efficient, and precise operations across all aspects of energy production, transmission, and usage. This will enable the transportation and energy systems to be flexibly matched in both time and space.

Economic Efficiency. By real-time sensing and intelligent control of the operational status of transportation infrastructure, vehicles, and energy systems, the optimal solutions for the safe, stable, and efficient flow of traffic and energy can be provided, significantly reducing costs and enhancing economic efficiency[4].

2.2 Research on the Architecture of Self-Sufficient Energy Systems for Expressways

(1) Connotation of Self-Sufficient Energy Systems in Transportation.

The self-sufficient energy system for highway transportation refers to an integrated energy system capable of achieving comprehensive energy utilization and self-sufficient energy supply within the highway transportation network. With the rapid development of renewable energy generation technologies, such as photovoltaic (PV) and wind power, constructing a green, comprehensive energy system that supplies renewable energy to highway operations, service areas, roads, bridges, and tunnels is not only technically and economically feasible but also provides significant reference value for the development of new self-sufficient green highways. A green energy system, characterized by self-sufficient energy supply, can reduce the cost associated with traditional power supply infrastructures. [5]

(2) Research on the Architecture of Self-Sufficient Energy Systems.

The architecture of self-sufficient energy systems is illustrated in Figure 1. The highway transportation self-sufficient energy system is a diversified and complex system that integrates multiple attributes such as source, grid, load, and storage. It includes a significant amount of renewable energy sources like wind and solar power, as well as large-scale energy storage equipment like batteries and supercapacitors. These systems supply power to transportation energy tools through AC/DC grid networks[6].

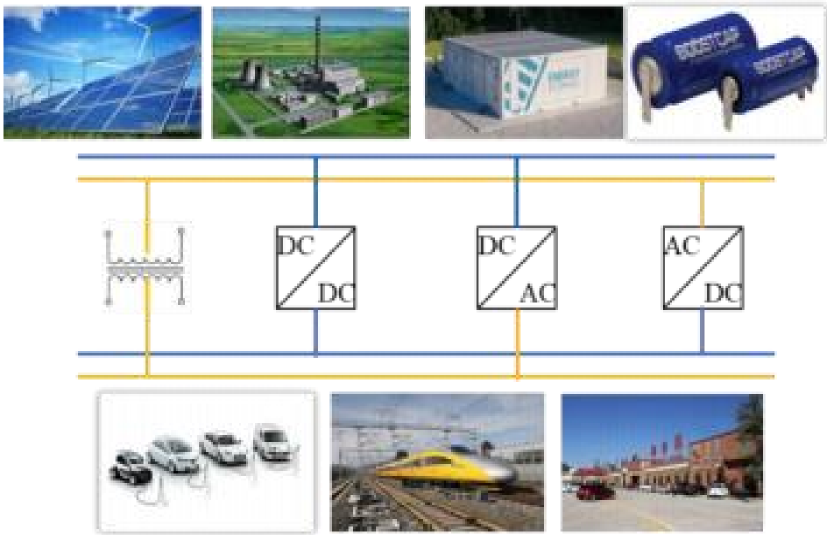

Fig. 1. Architecture of Self-Sufficient Energy Systems

The architectural characteristics of self-sufficient energy systems are mainly reflected in the following three aspects[7]:

1) Diversity in Energy Demand Fulfillment: The system can meet various grid energy demands with different characteristics. It can efficiently absorb wind and solar energy, provide load shifting, and satisfy lower-value energy demands of the grid. Simultaneously, it can also cater to high-demand energy scenarios like improving power quality and UPS systems;

2) Optimized Energy Dispatch and Combination: As the transportation energy system evolves, the interaction capabilities between different types of vehicles and the grid will significantly improve. By considering the energy demands of the system, the flexible dispatch of resources like electric vehicles and storage systems based on their characteristics and prioritization can effectively optimize the combination of different energies, thereby achieving real-time dispatch;

3) Flexible Energy Utilization in Spatiotemporal Dimensions: The transportation energy system integrates a large amount of storage equipment and distributed resources. The diversity in transportation modes with different characteristics allows for the flexible utilization of different energies across time and space dimensions, effectively enhancing the flexibility of the grid.

3 Research on Key Technologies of Expressway Traffic-Energy Integration

3.1 Research on Microgrid Planning Methods for Traffic-Energy Integration Based on Distributed Renewable Energy

The historical output data of wind farms contain inherent statistical regularities, while the temporal and autocorrelation characteristics of wind speeds in the wind farm area, as well as information on wind speed changes (such as long-term trends, seasonal variations, and periodic changes), are well preserved in the historical output data. However, due to the vast amount of historical wind power output data, it is impractical to include every day's output data in the planning system for calculations. Therefore, clustering methods can be used to reduce the number of scenarios, allowing a small number of representative scenarios to achieve the effects of many more, thereby improving computational efficiency[8]. The process of daily wind power output scenarios and their probability distributions is illustrated in Figure 2.

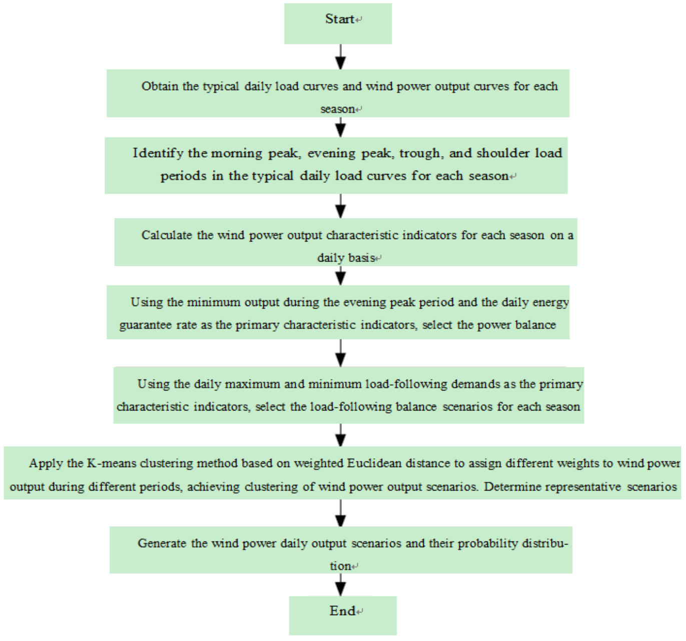

Fig. 2. Flowchart of Daily Wind Power Output Scenarios and Their Probability Distributions

3.2 Research on Key Technologies for Stable Operation of Photovoltaics Along Expressways[9]

The stability of photovoltaic (PV) systems along highways is analyzed using the MIDAS/GTS numerical simulation software and FLAC3D software. Below is an outline of the key technical aspects:

(1) Calculation Conditions and Assumptions

The model assumes that the top surface is free, while the other five surfaces are constrained to prevent normal displacement. For effective numerical simulation, given the complexity of the surrounding environment and material deformation mechanisms in actual engineering projects, the following assumptions are made:

(a) The construction site surface and soil layers are assumed to be horizontally distributed. In the absence of a geotechnical report, soil material parameters are referenced from similar engineering projects.

(b) Steel pipes are treated as isotropic elastic materials.

(c) All soil layers are assumed to be isotropic and continuous elastoplastic materials, modeled using a modified Mohr-Coulomb constitutive model.

(d) The stress-strain relationship of the strata and materials is assumed to vary within the elastoplastic range.

(2) Model Dimensions and Mesh Division

Based on the construction drawings and relevant engineering data for the Zaozhuang—Heze Expressway energy-transportation integration demonstration project, the geometric shape of the project site and the distribution of the foundation soil layers were appropriately simplified. A three-dimensional numerical analysis model was established using MIDAS/GTS software. The width of the subgrade soil body was set to three times the distance between the photovoltaic panel support columns. The depth of the original soil layer at the bottom of the model was set to 20 meters, meeting the requirement to neglect boundary effects. The model dimensions are 80m (length) × 48m (width) × 30m (height). To ensure calculation accuracy, the mesh was divided using a linear gradient (length) method. By inputting the lengths of the initial and final element lines, the positions of the nodes were automatically set through linear interpolation. This approach achieved a relatively dense mesh around the Furong Road tunnel and the Hefei Ring Expressway, with a relatively sparse mesh at the boundaries. The overall mesh division of the numerical simulation model is shown in Figure 3.

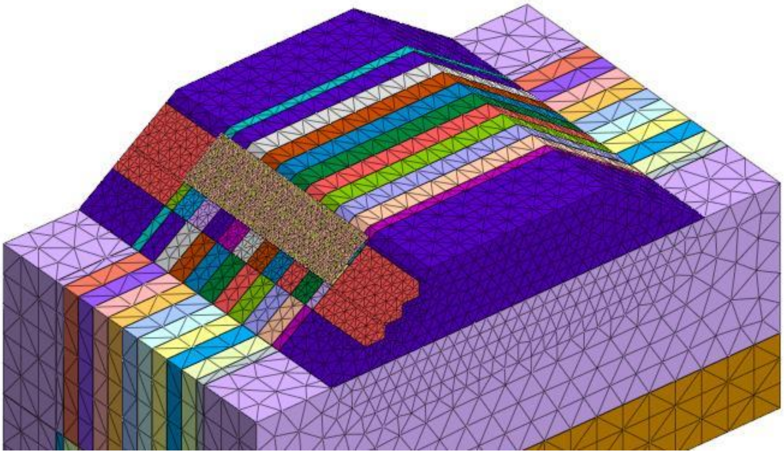

Fig. 3. Model Mesh Division Diagram

4 Research on Comprehensive Solutions for Expressway Traffic-Energy Integration

4.1 Integrated Solutions for Traffic-Energy Integration

In the planning phase, comprehensive considerations should include capacity demand, electrification technology pathways, energy demand, renewable energy resources, large grid support capacity, and economic factors. An integrated approach to planning energy supply, energy use, and energy receiving facilities should be adopted to ensure efficient land use and enhance the self-sufficiency rate of green energy.

4.2 Comprehensive Solutions for (Near) Zero-Carbon Service Areas

4.2.1 Green and Low-Carbon Technologies.

Integrated Source-Grid-Load-Storage Technology[10]

(1) Clean Energy Development

The development of clean energy in service areas leverages multi-energy complementary technologies, which maximize the advantages of various clean energy sources available in the region (such as solar and wind energy). This approach strengthens efficient resource processing, conversion, and integrated utilization to achieve cleaner and greener energy consumption in service areas.

(a) Photovoltaic Carports

Construct single/double cantilevered rain shelters with photovoltaic carports installed on top. The installation method should be a flat layout, considering both functional attributes and aesthetic requirements of the carports. The example diagram of the photovoltaic carport is shown in Figure 4.

Fig. 4. Photovoltaic Carport

(b) Rooftop Photovoltaics

Rooftops will utilize 545Wp conventional photovoltaic modules installed in alignment with the roof slope. The photovoltaic modules on the rooftops of the comprehensive building, automotive repair, mechanical and electrical rooms, and garbage stations should be laid at the optimal tilt angle. The example diagram of the rooftop photovoltaics is shown in Figure 5.

Fig. 5. Rooftop Photovoltaics

(c) Vertical Axis Wind Turbines

Vertical axis wind turbines will be deployed in service areas for wind power generation, with the turbines located at the entrance of the service area. These turbines will be designed as landscape features. The example diagram of Vertical Axis Wind Turbine is shown in Figure 6.

Fig. 6. Vertical Axis Wind Turbine

(2) Smart Grid Construction

In stable energy consumption areas, a “self-generated and self-consumed” principle will be applied. Clean energy generation systems will be directly integrated into the internal distribution network of service areas, toll stations, and other stable load demand areas. Through the deployment of smart microgrids and intelligent control systems, the goal is to maximize energy security for the traffic system and local consumption of clean energy, achieving a zero-carbon service area. The schematic diagram of smart microgrid construction is shown in Figure 7.

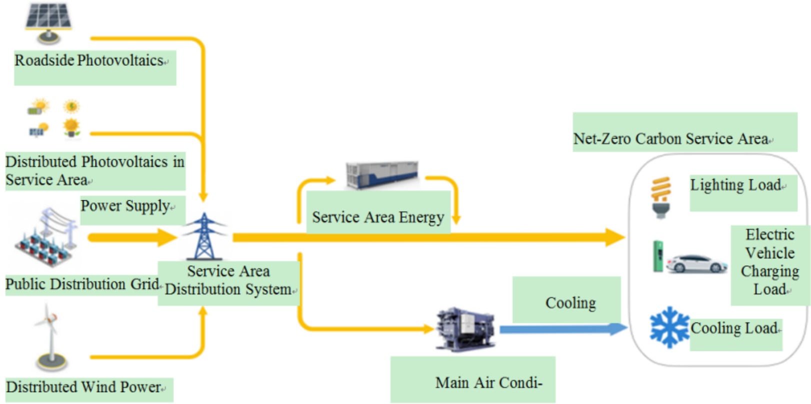

Fig. 7. Schematic Diagram of Smart Microgrid Construction

(3) Clean Energy Consumption

Expressway energy consumption primarily includes the energy needs of service (infrastructure) facilities such as tunnels, service areas, and toll stations, as well as the energy consumption of vehicles and road-related industries.

Charging Station Construction Plan: Install photovoltaic carports at small vehicle parking spaces within service areas, with integrated charging stations. The carports will be equipped with energy storage modules, and the photovoltaic-generated electricity will be prioritized for use in charging stations, enabling self-generation and self-consumption.

Battery Swapping Station Construction Plan: Establish new energy vehicle battery swapping stations on vacant land in service areas. Each swapping station will have parking spaces and several high-voltage batteries, offering continuous battery replacement services for drivers through cloud-based scheduling.

(4) New Energy Storage Systems

Energy storage facilities will be configured with the goal of achieving 100% pure green electricity supply in service areas and meeting local energy storage requirements. These facilities will participate in peak shaving and valley filling of the power grid to generate revenue or use excess photovoltaic electricity for charging and discharging to create additional income.

4.2.2 Digital Intelligent Control Technology[11-12].

(1) Integrated Smart Control Platform for Transportation and Energy

The integrated smart control platform for transportation and energy utilizes advanced technologies such as "big data, IoT, and digital twins" to achieve a seamless integration of energy flows, traffic flows, application platforms, and physical infrastructure.

(2) Smart Power Station Operation and Maintenance

The smart operation and maintenance module integrates IoT, wireless transmission, and cloud services with operational maintenance activities. It provides a complete intelligent operation and maintenance solution, including task assignment, diagnosis, and recovery. This system can automatically issue maintenance work orders for fault alarms, quickly pinpoint problem areas, reduce analysis time, and enhance the efficiency and timeliness of maintenance operations.

(3) Smart Parking System

The smart parking system employs high-mounted cameras to identify the occupancy status of parking spaces and vehicle types, track the traffic flow in service areas, alert abnormal parking conditions, collect license plate information, and guide parking.

(4) Smart Street Lighting

The smart street lighting system includes an intelligent lighting management system, smart information release system, intelligent sensing system, video surveillance system, and emergency alert system.

(5) Smart Cashier System

The smart cashier system supports the promotion of the "mall management" model in service areas, adhering to the principles of "unified management, professional operation, profit sharing, and risk sharing." The service area provides the commercial space, while merchants conduct their business. The service area adopts a revenue-sharing mechanism with a minimum guaranteed base income.

(6) Unmanned Smart Supermarket

The unmanned smart supermarket enables cashier-less, unattended operations, offering 24/7 service. It leverages computer vision technology to accurately recognize shopping behaviors, supports dual self-payment methods via WeChat and Alipay, and eliminates the need to wait in line for manual checkout.

5 Conclusion

In the face of the complex and rapidly changing internal and external environments, the integration of energy and highway transportation presents both significant opportunities and numerous challenges. This research, grounded in the current status and trends of energy and highway transportation integration, undertakes a comprehensive study of the technological system, key technologies, overall solutions, and policy mechanisms required for this integration.

The goal is to develop a technical framework for the application of clean energy within the highway transportation sector, proposing a technology architecture based on the integration of energy and highway transportation. This includes the design of energy self-sufficient systems for typical transportation modes, along with the foundational infrastructure—the "four beams and eight pillars"—necessary for the transportation-energy integration field.

Building upon the traditional highway power supply system, this project incorporates renewable energy, energy storage technology, and microgrids. It introduces a planning methodology for transportation-energy integrated microgrids based on distributed renewable energy, maximizing the use of transportation spaces for renewable energy development. The project aims to overcome the key technical challenges of comprehensive transportation-energy integration, promoting the deep integration of renewable energy with expressways. This effort is expected to realize green, intelligent transportation and advance carbon peak initiatives in the transportation sector.

Through research on the configuration methods for new energy and energy storage, combined with the construction of demonstration projects, this project seeks to establish an integrated planning and operation system for "source-grid-load-storage." It will also develop large-scale photovoltaic application solutions for expressways and near-zero-carbon service area solutions, contributing to the overall strategy for the integration of energy and highway transportation.

Fund Project

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