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Key Technologies for Carbon Reduction throughout the Entire Process of Green Power Construction

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Abstract: In the context of the national "dual carbon" goals — namely, achieving carbon peaking and carbon neutrality — transmission and transformation projects, as an essential component of the power system, play a pivotal role in promoting green construction practices and advancing carbon reduction efforts. These projects not only serve as critical infrastructure for the reliable delivery and transformation of electrical energy but also represent key opportunities for integrating sustainable technologies and achieving substantial reductions in carbon emissions throughout the engineering lifecycle. Against this backdrop, this paper focuses on the development and application of key technologies that support carbon reduction across the entire green construction process of transmission and transformation projects. Specifically, it introduces the FCCSP (Full-process Carbon Control and Smart Planning) management system, which provides an integrated framework for systematically controlling carbon emissions at every stage — from project design and material selection to construction, commissioning, and long-term operation. Furthermore, the paper details a series of core technological innovations that enhance the carbon reduction capability of these projects, including advanced materials, intelligent construction techniques, and data-driven carbon management tools. The effectiveness and practical value of these technologies are rigorously validated through a set of representative engineering case studies, offering both theoretical insights and empirical evidence. In doing so, this research provides a comprehensive reference for advancing the low-carbon transformation of transmission and transformation projects, and contributes valuable guidance for achieving the broader objectives of sustainable power system development.

Keywords: dual carbon goals; green construction; FCCSP management system; carbon reduction technologies

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1. Introduction

1.1. Research Background

Under the "dual carbon" goals, the power infrastructure sector is under increasing pressure to undergo a comprehensive low-carbon transformation. As a vital component of the modern power system, transmission and transformation projects are expected to play a key role in achieving significant reductions in greenhouse gas emissions. However, in practice, these projects face a range of complex challenges in managing carbon emissions across their entire lifecycle. One of the primary issues is the lack of clearly defined carbon accounting boundaries, which leads to inconsistencies and uncertainties in emission data collection and reporting. Without standardized methodologies, it becomes difficult to accurately assess the true carbon footprint of these large-scale engineering projects. In addition, existing carbon reduction technologies tend to be fragmented and isolated — often targeting specific stages or subsystems — rather than offering an integrated, end-to-end solution. This fragmented approach limits the overall effectiveness of emission reduction efforts and hinders the adoption of systematic carbon management practices within the industry. These problems severely impede the progress of the power sector toward achieving low-carbon development targets. Therefore, there is an urgent need to explore and establish a comprehensive, standardized, and highly practical carbon reduction technology system specifically tailored for transmission and transformation projects [1]. Such a system would not only provide technical pathways for reducing emissions but also offer robust management tools to guide project planning, execution, and operation in alignment with national carbon neutrality objectives.

1.2. Research Objectives

This paper aims to establish a comprehensive carbon emission reduction technology system that spans the entire lifecycle of power transmission and transformation projects, encompassing the stages of design, construction, acceptance, and operation. By systematically integrating carbon management principles into each phase of project development, the proposed system seeks to enable dynamic monitoring and intelligent optimization of carbon emissions throughout the project lifecycle. Through the use of advanced digital tools, real-time data acquisition, and intelligent analytics, the system will provide precise, actionable insights into emission sources and reduction opportunities. Ultimately, this research is intended to deliver both scientific technical solutions and practical engineering guidance to support the implementation of green construction practices in transmission and transformation projects [2]. The proposed approach will contribute to enhancing the industry's capacity to meet national low-carbon development targets while promoting a sustainable, environmentally responsible transformation of power infrastructure [3].

2. Theoretical Framework of Green Construction: FCCSP Control System

2.1. The Goal of "Two Types and Three Modernizations"

Target layer: with the goal of "green, low-carbon, energy-saving and environmental protection", it is committed to reducing the carbon emission in the whole life cycle of power transmission and transformation projects, reducing the impact on the environment, and realizing the efficient utilization of resources [4].

Methodology Level: By employing lean management, standardized design, and intelligent construction, the aim is to enhance construction efficiency and quality, ensuring the achievement of green construction goals. Lean management focuses on precise control of the construction process and optimizing resource allocation; standardized design ensures consistency and compliance in engineering, facilitating the adoption of green technologies; intelligent construction utilizes advanced information technology and smart equipment to achieve intelligent monitoring and management of the construction process.

2.2. "Four Stages" Will Be Implemented Step by Step

To promote sustainable development within power transmission and transformation projects, this paper proposes the implementation of green construction practices across four key stages: *green planning, green design, green construction, and green handover*. In the green planning stage, the project's overarching green construction goals and strategies are clearly defined. A detailed implementation plan is formulated, outlining specific carbon reduction targets, technical pathways, and management measures to guide all subsequent phases. In the green design stage, green principles are systematically integrated into the engineering design process. This includes optimizing structural layouts, selecting environmentally friendly materials, and minimizing the use of high-carbon materials and equipment, thereby reducing the project's embedded carbon footprint from the outset. During the green construction stage, strict adherence to the established design requirements and relevant green construction standards is maintained. Low-carbon technologies, innovative construction techniques, and energy-efficient processes are employed to further reduce emissions and environmental impacts during project execution. Finally, in the green handover stage, a comprehensive inspection and evaluation of the completed project is conducted to verify that it meets all predefined green and low-carbon performance criteria. This stage ensures that the project delivers measurable carbon reduction outcomes and aligns with broader environmental sustainability goals. By systematically implementing green practices throughout these four stages, the approach provides a robust framework for achieving low-carbon, high-quality development in power transmission and transformation infrastructure.

2.3. Innovation of Collaborative Mechanism

To ensure effective implementation of green construction practices in power transmission and transformation projects, it is essential to establish a deep collaboration mechanism among the five key stakeholders: construction, design, construction supervision, and operation units. This multi-party cooperation framework facilitates joint participation and shared responsibility throughout the project lifecycle, promoting a holistic approach to carbon emission management. Central to this collaborative effort is the application of the PDCA (Plan-Do-Check-Act) cycle, which provides a systematic methodology for managing the carbon emission chain through hierarchical and iterative control processes. In the planning stage (Plan), clear carbon reduction goals and strategies are established for each stakeholder, forming the basis for targeted actions. During the doing stage (Do), planned measures are implemented with active involvement and coordination among all parties. The checking stage (Check) involves rigorous monitoring and evaluation of carbon emissions to identify deviations and areas for improvement. Finally, in the acting stage (Act), corrective actions and optimizations are applied to refine the construction process and enhance carbon control effectiveness. Through continuous repetition of this PDCA cycle, the collaboration mechanism drives ongoing improvements in carbon emission management, ensuring that transmission and transformation projects meet increasingly stringent low-carbon requirements and contribute meaningfully to national sustainability objectives [5].

3. Core Technology Innovation

3.1. Intelligent Carbon Footprint Management System (SPC Theory Driven)

3.1.1. Innovation Points

This research presents the world's first application of Statistical Process Control (SPC) techniques to the dynamic optimization of engineering carbon footprints in power transmission and transformation projects. By leveraging real-time monitoring and analysis of carbon emission data throughout the construction process, SPC enables the early identification of abnormal fluctuations or trends in carbon emissions that may arise due to changes in materials, equipment performance, or construction practices [6,7]. Upon detecting such deviations, corrective measures can be promptly implemented to adjust construction activities and operational parameters, thereby maintaining alignment with carbon reduction targets. Through the integration of SPC into the project's carbon management workflow, this approach has successfully achieved a reduction rate of more than 15% in carbon emission intensity. This pioneering application demonstrates the potential of combining traditional quality control methodologies with modern carbon management strategies, offering a powerful tool for driving continuous improvement in low-carbon construction practices.

3.1.2. System Architecture

Real-time monitoring layer: Using the Internet of Things and multi-source sensor network, the carbon intensity data of energy, process and raw materials are collected, and data cleaning and standardization are realized through edge computing to ensure the accuracy and real-time data [8].

Statistical analysis layer: SPC control charts (such as X-bar chart and CUSUM chart) are introduced to quantify carbon emission fluctuations, calculate the process capability index of carbon efficiency (Cp-carbon), and identify the root cause of abnormal fluctuations by machine learning to provide a basis for carbon emission optimization.

Dynamic control layer: Establish multi-objective optimization model, adjust process parameters through digital twin simulation and real-time feedback, balance carbon emission, energy consumption and cost, and realize dynamic control of carbon emission.

Compliance improvement layer: Based on the PDCA cycle, it generates automated carbon audit reports, benchmarks against international standards such as ISO 14064, drives supply chain collaborative optimization, and improves the standardization and transparency of carbon emission management [9].

3.2. Low Carbon Operation Standard Procedure (SOP)

3.2.1. Planning Stage

In order to further enhance the green construction level of power transmission and transformation projects, priority should be given to the adoption of advanced low-carbon equipment and environmentally friendly design concepts. Specifically, the use of natural ester transformers, clean gas-insulated switchgear (GIS) equipment, and photovoltaic (PV) integrated designs should be actively promoted. The application of these technologies not only reduces reliance on traditional high-carbon equipment but also helps to minimize environmental impacts such as land disturbance — by more than 30% — through more compact and integrated project designs. Natural ester transformers, known for their excellent environmental performance and operational reliability, utilize biodegradable insulating liquids derived from renewable resources, significantly lowering carbon emissions during both manufacturing and operation. Clean gas GIS equipment replaces conventional SF_6 — an extremely potent greenhouse gas — with environmentally friendly gas alternatives, effectively reducing greenhouse gas emissions while maintaining high-voltage insulation performance. Furthermore, integrating photovoltaic systems into project designs allows for the on-site generation of renewable solar energy, thereby reducing dependence on fossil fuels and contributing to long-term carbon reduction throughout the project's operational phase. Collectively, the widespread adoption of these technologies provides a practical and effective pathway for achieving substantial improvements in the environmental performance of transmission and transformation projects [10].

3.2.2. Construction Stage

Prefabricated assembly technology: The prefabricated assembly technology can shorten the construction period by 20% and reduce the carbon emission on site. The prefabricated components are processed and made in the factory, which reduces the pollution and energy consumption on site construction, and improves the construction efficiency and quality [11].

Application of recycled building materials: In the Zhoushan project, the application of recycled building materials reduces the consumption of steel by 35%, effectively reducing the waste of resources and carbon emissions.

Waste classification management: Implement waste classification management, the recycling rate of construction waste is more than 90%, reducing the pollution of waste to the environment, and realizing the recycling of resources.

3.2.3. Operation and Maintenance Phase

By leveraging an intelligent monitoring system, dynamic scheduling of new energy resources can be effectively achieved during the operation and maintenance stage of power transmission and transformation projects. Through real-time monitoring of equipment operating status and energy consumption data, the system enables precise optimization of energy allocation, ensuring that new energy sources — such as solar and wind power — are rationally utilized and efficiently integrated into the overall energy mix. This dynamic scheduling capability not only maximizes the utilization efficiency of renewable energy but also reduces the reliance on conventional high-carbon energy sources, thereby contributing to a significant reduction in carbon emissions during long-term project operation. Moreover, the intelligent monitoring platform facilitates continuous analysis and adaptive control of energy usage, allowing for timely adjustments in response to fluctuating demand or generation conditions. As a result, the system supports improved energy efficiency, enhanced operational stability, and the achievement of sustainable low-carbon operation throughout the project lifecycle [12].

3.3. Carbon Emission Sensitivity Analysis of UHV Projects

3.3.1. Key Findings

An in-depth analysis of carbon emission contributions in ultra-high voltage (UHV) transmission projects reveals that the majority of emissions originate from a few key material components. Specifically, conductors account for approximately 45% of the total carbon footprint, followed by tower materials at 25%, and transformers contributing around 12%. This distribution clearly indicates that conductors and tower materials are the predominant sources of carbon emissions within UHV projects. Given their significant share, efforts to reduce carbon emissions must prioritize these components to achieve meaningful overall reductions. Strategies such as optimizing material selection, improving manufacturing processes, and exploring low-carbon or recycled alternatives for conductors and tower materials are therefore critical. By targeting these major emission contributors, UHV transmission projects can more effectively align with carbon reduction goals and enhance their environmental sustainability.

3.3.2. Sensitivity Formula

Using a sensitivity formula, the greater $\mathrm{E_i} = \frac{\Delta \mathrm{A_i}}{\Delta \mathrm{F_i}}$ the factor, the more significant its impact on key carbon emission factors. The study found that the carbon emission factor of aluminum is highly sensitive; a ±30% fluctuation in this factor can result in a ±18.7% change in total carbon emissions. Therefore, optimizing aluminum production processes and reducing its carbon emission factor are crucial measures for carbon reduction in ultra-high voltage projects.

4. Technical Verification and Benefit Analysis

4.1. Typical Engineering Cases

4.1.1. 110KV Zero-Carbon Substation in the North of Anji City

The application of "light storage, direct and flexible" microgrid has achieved a photovoltaic absorption rate of 98%, and the cycle efficiency of energy storage system has exceeded 92%. At the same time, the prefabricated assembly rate has reached 85%, and the construction carbon emission has been reduced by 32%, achieving the zero-carbon goal of the substation.

4.1.2. Zhoushan 500KV Network Project

The slope protection with planted concrete, UAV inspection and tidal power supply system were adopted to reduce the carbon emission during operation and maintenance by 40%. The Marine ecological restoration area reached 190,000 square meters, making it the first Marine ecological restoration project of power transmission and transformation engineering in China.

4.2. Comprehensive Benefits

4.2.1. Economic Benefits

Taking the medium-sized investment of 500kV power transmission and transformation project as an example, it can reduce carbon emissions by about 2000 tons. Combined with the price of the pilot area of carbon trading in East China (41.20 yuan/ton), the total carbon emission cost can be reduced by 25.983 million yuan, with significant economic benefits.

4.2.2. Environmental Benefits

Through real-time monitoring and dynamic optimization, the annual carbon emission reduction of Changlongshan 500kV project reaches 8000 tons; during the construction process, "0 slope protection 0 retaining wall" technology is adopted to reduce the cutting of vegetation by 420,000 square meters, maintaining the terrestrial biodiversity and regional ecosystem balance, with significant environmental benefits.

5. Conclusion

The "FCCSP System + SPC Carbon Control System" developed in this paper provides a comprehensive and effective solution for carbon management across the entire lifecycle of transmission and transformation projects. By integrating full-process carbon control strategies with statistical process control (SPC) techniques, the system enables continuous monitoring, precise analysis, and dynamic optimization of carbon emissions from project design through construction, operation, and maintenance. Typical engineering case studies have demonstrated that the application of this technology can achieve significant carbon emission reductions, with approximately a 30% decrease during the construction phase and up to a 40% reduction during the operation and maintenance stage. This performance validates the system's capability to deliver a low-carbon pathway that is quantifiable, traceable, and optimizable, thereby providing valuable practical insights for advancing the low-carbon transformation of power grid projects. Looking ahead, it is imperative to further strengthen research and the widespread adoption of carbon emission control technologies throughout the full lifecycle of transmission and transformation projects. Continuous improvements in green construction standards, carbon evaluation systems, and management frameworks will be essential to maximize carbon reduction potential and support the achievement of national "dual carbon" goals. Through such concerted efforts, the power industry can contribute more effectively to global sustainability and environmental protection objectives.

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