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Research on the Green Value of Intelligent Operation and Maintenance of Power Equipment and the Synergy Effect of Industrial Chain under the Constraint of Double Carbon Target

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Abstract: *Under the background of environmental carrying capacity approaching the border, in the process of global energy reform, the "double carbon" strategy has profoundly reshaped the operation logic of the power industry. This paper focuses on the field of power equipment operation and maintenance, aiming at explaining the ecological effect of intelligent operation and maintenance technology and the role of industrial ecological reconstruction from a theoretical perspective. Based on system dynamics and life cycle theory, this paper analyzes the transformation mechanism of traditional paradigm to intelligent forecasting model under high carbon constraints, and constructs a multi-dimensional green value framework covering energy efficiency optimization, process emission reduction and resource life extension. At the same time, it deconstructs the interactive mechanism of vertical information feedback and horizontal knowledge spillover in the industrial chain, and demonstrates the network externalities caused by data sharing and standard unification. Intelligent operation and maintenance reduces the implied carbon emissions in the whole life cycle of assets, and breaks down barriers through the benefit synergy mechanism to maximize the overall carbon efficiency. This paper puts forward the evolution path of technological innovation and institutional incentive, and emphasizes that the establishment of incentive-compatible governance system is the key. The results provide theoretical basis for government policy formulation and enterprise supply chain strategy, and promote the power industry to a new stage of high-quality sustainable development, which has significant demonstration significance.*

Keywords: *Double carbon target; Electric power equipment; Intelligent operation and maintenance; Green value; Industrial chain coordination*

1. Introduction

Under the macro background of global warming and increasingly severe environmental crisis, the strategic goal of "peak carbon dioxide emissions and carbon neutrality" has profoundly reshaped the development logic of China's economy [1]. As the source of energy consumption and carbon emissions, the power industry's green and low-carbon transformation is the key hub to realize the national dual-carbon vision [2]. Power equipment is the core asset to maintain the stable operation of power grid, and the efficiency of its operation and maintenance mode is directly related to the energy utilization efficiency and the carbon footprint level of the whole life cycle [3]. For a long time, the operation and maintenance of power equipment in China still follows the traditional fault-oriented paradigm, and there are some problems such as over-maintenance, information islands and resource mismatch [4]. This management mode with high energy consumption and low responsiveness is gradually approaching the boundary of environmental carrying capacity, and it is difficult to adapt to the internal demand of refined and clean management of double carbon targets.

In recent years, intelligent operation and maintenance technology represented by digital twinning and edge computing has already been rapidly applied in the power production, which has provided technical possibilities for solving above contradictions [5]. Intelligent operation and maintenance can reduce the risk of unplanned downtime through predictive maintenance, which has significant potential for resource saving and emission reduction in theory [6]. The existing research on intelligent operation and maintenance mostly focuses on the application effect evaluation of a single technology node or the algorithm improvement at the micro level, and few documents systematically explain its comprehensive "green value" composition under the constraint of double carbon in theory [7]. Power

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equipment involves many subjects, such as design, manufacture, operation, decommissioning, etc. The existing research often separates the links, ignoring the economies of scale and network externalities generated by data interoperability and standard collaboration between the upstream and downstream of the industrial chain. In this study, the green value of intelligent operation and maintenance of power equipment and the synergy mechanism of industrial chain under the constraint of double carbon target are discussed in depth.

2. Paradigm transformation logic of power operation and maintenance under double carbon constraints

The setting of double carbon target essentially constitutes a strong external constraint on the traditional power operation and maintenance model, forcing the industry to reconstruct the management boundary of asset life cycle. From the perspective of environmental economics, the internalization of carbon emission costs has significantly increased the opportunity cost of extensive operation and maintenance [8]. The traditional mode of relying on manual experience and repairing after the event has serious information asymmetry and decision-making lag, which leads to the equipment being in the non-optimal energy efficiency range for a long time, resulting in a lot of hidden energy waste and carbon emissions.

This pressure transmission mechanism gave birth to the paradigm shift from “passive response” to “active prediction”. Based on cyber-physical systems theory, intelligent operation and maintenance realized the visualization and predictability of equipment status through real-time data acquisition and algorithm deduction [9]. This greatly reduces the resource loss caused by excessive maintenance, and avoids restarting carbon emissions caused by catastrophic failures through precise intervention. Theoretically, this transformation embodies the combination of the substitution effect of technology on natural capital and the principle of economies of scale.

The construction of the mapping relationship between virtual space and physical entities based on digital twinning technology supports the operation and maintenance strategy to be previewed without carbon risk in the simulation environment. This dynamic optimization logic ensures that the running track of the equipment always approaches the Pareto optimal frontier. Therefore, the paradigm transformation under the constraint of double carbon is essentially to correct market failure by digital means, and realize the double leap from pure economic rationality to ecological economic rationality in the premise of ensuring power grid security.

3. Deconstruction of multidimensional connotation of green value of intelligent operation and maintenance

The green value of intelligent operation and maintenance is a multidimensional value set based on system dynamics and life cycle theory, and its connotation goes beyond the traditional terminal energy consumption management, emphasizing the systematic efficiency revolution under technology empowerment [10]. From the perspective of energy flow, energy efficiency improvement is the basic value form. There is information asymmetry in traditional operation and maintenance, which causes the equipment to run in inefficient working conditions for a long time and produces a lot of invalid losses. Through state monitoring and closed-loop control, intelligent operation and maintenance dynamically adjusts the operation parameters, making the equipment working point approach the optimal curve of theoretical energy efficiency, maximizing the marginal utility of energy utilization rate and reducing the energy input per unit output from the source. From the perspective of carbon footprint, process emission reduction constitutes a direct contribution. This includes not only the reduction of operating power, but also the hidden carbon emissions caused by unplanned downtime, high-carbon restart and emergency repair due to reliability improvement. Predictive maintenance changes ex post remedy into ex ante intervention, which significantly reduces the carbon emission intensity per unit output of the whole operation and maintenance chain, and reflects the endogenous governance of carbon cost by technology. The value of prolonging life from the perspective of resource reuse reflects deep benefits. Accurate evaluation avoids the damage to equipment caused by excessive maintenance and effectively prolongs the life of assets. From a macro point of view, this means delaying the capital investment of new equipment manufacturing, reducing the hidden carbon emissions of high energy consumption in upstream production links, and reducing the environmental load of waste treatment.

To sum up, the three dimensions of energy saving, carbon emission reduction and resource

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recycling are coupled with each other, which jointly define the green value boundary of intelligent operation and maintenance, that is, the organic unity of minimizing energy consumption, internalizing environmental impact and optimizing resource allocation.

4. Interactive mechanism of vertical coordination and horizontal coupling of industrial chain

Vertical synergy and horizontal coupling of industrial chain constitute the system foundation of green transformation under the background of double carbon, and they support each other to break through the capability boundary of a single enterprise. There is significant information complementarity between upstream equipment manufacturers and downstream power grid operators, which provides a theoretical premise for vertical integration. In the vertical dimension, the separation of design and operation and maintenance in the traditional mode leads to insufficient matching between the initial design and the actual working conditions, while intelligent operation and maintenance enables manufacturers to optimize the next-generation product design according to the actual operating conditions by establishing a full life-cycle data channel, while operators use digital files provided by the manufacturing end to achieve predictive maintenance. This two-way feedback mechanism effectively reduces the cost of trial and error and improves the overall energy efficiency of assets. In terms of risk sharing, the vertical contract design allows both parties to share the uncertain benefits in the early stage of technical iteration, thus achieving interest compatibility. The horizontal coupling between enterprises in the same industry can not be ignored. Faced with the common pressure of emission reduction, there is room for cooperation and game between competitors. By formulating unified equipment health assessment standards and data interface specifications, enterprises can break the information island and significantly reduce market transaction costs. The horizontal platform also promotes the spillover effect of tacit knowledge and forms a unique network externality, which makes the accumulation of technological innovation of a single enterprise turn into industrial public goods and greatly accelerates the diffusion efficiency of green technology in the whole industrial chain.

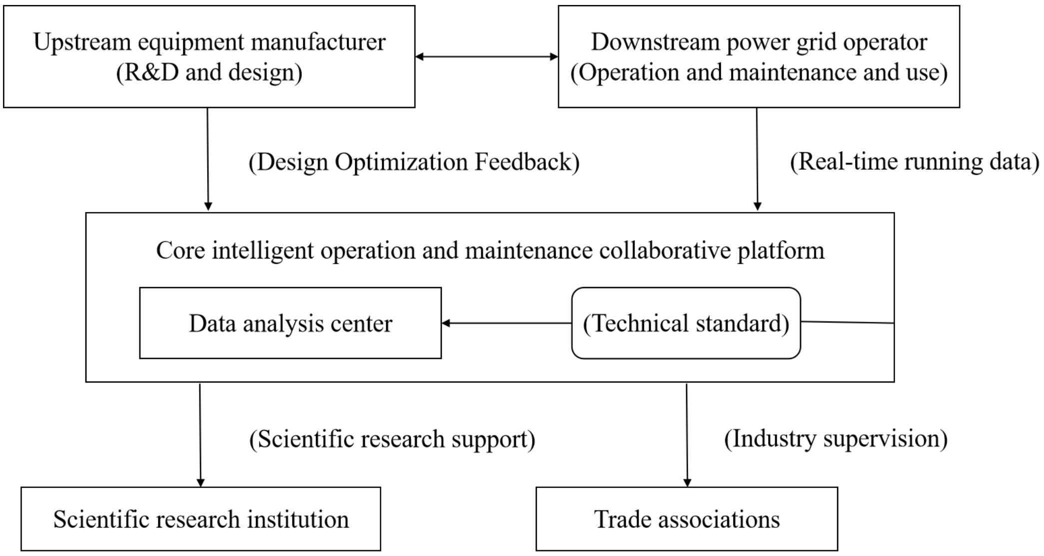

Figure 1 Intelligent operation and maintenance collaborative interaction mechanism model of power equipment industry chain

The model in Figure 1 defines the interaction path between data flow and value flow among multi-agents, and reveals the mechanism of synergistic effect. This architecture shows that the synergistic effect is not a one-way transmission, but the result of multi-node resonance. Finally, the deep integration in the vertical direction solves the problem of technical adaptability, and the extensive coupling in the horizontal direction realizes the economies of scale. Together, the two will internalize the scattered emission reduction responsibilities into the common strategy of the industrial chain and form a sustainable green value chain.

5. System evolution power and collaborative governance path

To achieve the zero-carbon goal of intelligent operation and maintenance of power equipment, a dual-engine system of technological innovation and institutional norms with mutual promotion should

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be established together to jointly shape the supply side underlying logic of industry evolution. Technological innovation promotes the willingness to adopt green technology by reducing marginal costs, while institutional norms set the boundaries of behavior by defining property rights and internalizing externalities. At the level of theoretical deduction, simple market mechanism often faces the risk of failure. Therefore, it is necessary to introduce policy tools to correct it, in which carbon trading mechanism can directly quantify the financial cost of carbon emissions, forcing high-energy equipment operators to seek low-carbon alternatives. This price signal is transmitted to the upstream of the supply chain, which encourages manufacturers to optimize product design to reduce life-cycle emissions. At the same time, the green financial system lowers the capital threshold of green technology diffusion through differentiated financing costs and discount policies. When carbon price incentives and capital support form a joint force, the decision-making function of market players will fundamentally shift, making the green operation and maintenance strategy the optimal solution for rational economic people. In this process, the government, as the rulemaker, is responsible for maintaining the fairness and transparency of the market, while the trade association undertakes the function of standard coordination to ensure the compatibility and interoperability of data interfaces among different subjects, thus preventing technical barriers from hindering the evolution efficiency of the whole system.

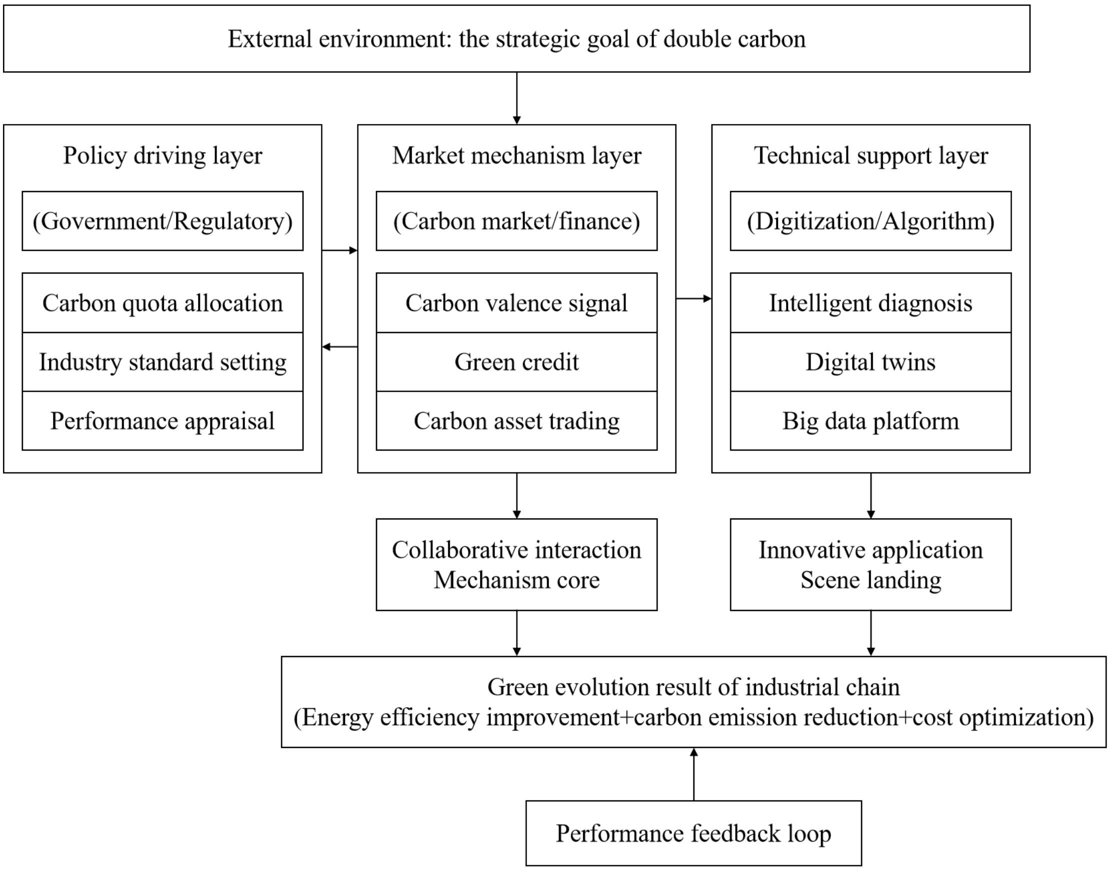

Figure 2 Multi-domain collaborative governance and evolution path framework for intelligent operation of power equipment

As shown in the track of evolution from initial to mature in figure 2, we need an internal policy-driven stage through a market autonomy stage. This framework avoids the lag of static policies and ensures that the governance system has the elastic characteristics of adapting to the rapid iteration of technology. In particular, it emphasizes the importance of inter-departmental coordination, that is, the policy consistency between energy authorities and environmental protection departments is the premise to prevent "fallacy of composition". The system will promote the transformation of power equipment operation and maintenance from a single cost center to a value creation center, and realize Pareto improvement of economic benefits and environmental benefits.

So the final evolution of systems will be to create a super-adaptive and data-centric zero-carbon ecosystem. In this system, all kinds of subjects are no longer passive executors, but co-builders who actively participate based on common interests. The key of collaborative governance is to design a set

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of incentive compatible contracts that can dynamically adjust parameters to ensure the balance between short-term investment and long-term income. With the improvement of carbon pricing mechanism and the improvement of intelligent algorithm accuracy, the traditional operation and maintenance mode will be completely reconstructed and replaced by a new industrial ecology based on value stream sharing.

6. Conclusions

On the basis of summarizing current state of the intelligent operation and maintenance of power equipment, and under the macro background of double carbon target, this paper systematically deduces a generation mechanism for green value from the intelligent operation and maintenance as well as its important synergistic effect with industrial chain. It is considered that intelligent operation and maintenance is essentially a subversion of traditional asset management logic, which uses digital technology to transform fuzzy environmental responsibility into accurate controllable variables. Green value has multi-dimensional compound characteristics. This is reflected in the direct saving of operating power, but also in the carbon emission of new capacity avoided by extending the life of equipment through accurate maintenance, which reflects the landing of the concept of circular economy in the field of power infrastructure. This kind of value reconstruction requires breaking the old thinking that only focuses on operating costs and establishing a full-cost accounting system that includes hidden carbon costs. Synergistic effect of industrial chain is the key to value amplification. Vertically, the closed loop of design and operation and maintenance data enables manufacturers to optimize product energy efficiency and avoid the dilemma of "production is backward". Horizontally, cross-enterprise standard interoperability forms the positive externality of the network, which reduces the innovation risk and marginal cost of a single subject. This kind of collaboration is not a spontaneous market behavior, and there is often a separation between trust barriers and standards, so the intervention of top-level design is needed. The governance path needs to give consideration to both motivation and constraints. Simply relying on technological progress can't overcome the shortage of low-carbon investment caused by capital profit-seeking. We must rely on the price discovery function of carbon trading market and the financing guidance of green finance to form an incentive chain with compatible interests. At the same time, trade associations should promote the standardization of data interfaces to prevent the formation of new digital monopoly.

In summary, the zero-carbon transformation intelligent operation and maintenance of power equipment is a complex system engineering involving technical iteration, business model innovation and institutional rules improvement. The theoretical framework constructed in this paper reveals the coupling relationship between various elements and points out the direction from passive compliance to active ecological co-construction. Future research can further explore the balance threshold between energy consumption and emission reduction benefits of the algorithm, which is a deep topic worthy of attention in academic circles. This provides a logical starting point for the subsequent formulation of relevant policies, and also provides an analytical tool for power companies to identify competitive advantages in the double-carbon wave, marking the shift of focus from the perspective of single equipment to the ecological perspective of the whole industry chain, ensuring the integrity of the paper.

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