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Synergistic Optimization of Renewable Energy Supply Chains under the Dual Carbon Goals

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Abstract **Original Research Article**

Under China's strategic commitment to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 (the "Dual Carbon Goals"), renewable energy enterprises face unprecedented pressure to simultaneously expand capacity, reduce costs, enhance supply chain resilience, and minimize carbon footprints. This study systematically investigates supply chain synergy optimization for wind and solar power enterprises within the Dual Carbon policy framework. Employing a multi-method approach integrating literature review, system analysis, and a case study of LONGi Green Energy, this research identifies three core synergy barriers: geographic fragmentation and policy decoupling, carbon traceability credibility crises, and inherent conflicts among efficiency, decarbonization, and resilience objectives. A three-tier collaborative optimization framework is proposed, comprising: (1) an information synergy layer based on blockchain-enabled carbon data pools; (2) an operational synergy engine integrating multi-objective optimization models with dynamic carbon taxation and shared warehousing; and (3) a carbon synergy mechanism incorporating tiered supplier incentives and green transition funds. Empirical validation through the LONGi case demonstrates significant improvements: total supply chain costs reduced by 15.3%, lifecycle carbon emissions per watt decreased by 39.6%, and disruption recovery time shortened by 58.3%. This research contributes a "policy-geography-technology" three-dimensional synergy blockage theory, a tri-objective dynamic equilibrium model, and a responsibility-sharing carbon governance framework, offering both theoretical advancements and practical pathways for sustainable energy supply chain management.

Keywords: Dual Carbon Goals, Renewable Energy, Supply Chain Synergy, Carbon Traceability, Supply Chain Resilience, Blockchain, Multi-Objective Optimization, Green Supply Chain.

Chapter 1: Introduction

1.1 Research Background and Significance

1.1.1 Research Background

The escalating challenges of global climate change have made the transition to clean and low-carbon energy structures an international consensus. As a responsible major nation, China has clearly articulated its national strategy to "peak carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060." The realization of this ambitious goal hinges fundamentally on transformative changes in energy production, with the vigorous development of renewable energy sources—particularly wind and solar power—serving as a critical pathway [1]. National policies such as the *14th Five-Year Plan for Renewable Energy Development* have provided unprecedented opportunities for the renewable energy industry, with installed capacity continuing to grow at remarkable rates.

However, behind this vigorous growth, the supply chain systems of renewable energy enterprises are confronting increasingly prominent challenges and pressures:

(1) Dramatic Increase in Supply Chain Complexity: The manufacturing of renewable energy equipment is highly globalized, characterized by numerous supply chain nodes, wide geographical distribution, and high technical requirements. These systems are highly susceptible to international geopolitics, trade policies, logistics bottlenecks, and shortages of critical components, rendering coordination extremely difficult [2].

(2) Compulsive Pressure from the "Dual Carbon" Goals: The Dual Carbon goals demand not only cleaner energy production but also low-carbon operations across the entire energy industry chain. This imposes dual pressures on renewable energy enterprises: on one hand, they must rapidly expand production capacity to meet growing green electricity demand; on the other hand, their own supply chains face stringent carbon accounting, transparency, and reduction requirements. The control of overall supply chain carbon footprints has become a new rigid constraint and a focal point of synergy optimization.

(3) Cost and Efficiency Pressures: As subsidies are progressively phased out, the renewable energy sector is rapidly transitioning into an era of grid parity or even below-grid pricing, subjecting enterprises to immense cost control pressures [3]. The lack of effective coordination across supply chain nodes results in information silos, inaccurate forecasts, inventory redundancies or shortages, low logistics efficiency, and amplified bullwhip effects—all of which significantly inflate overall operational costs and weaken corporate competitiveness.

(4) Urgent Need for Supply Chain Resilience: In recent years, frequent global disruptive events and extreme weather conditions have highlighted the critical importance of supply chain resilience. Due to their globalized and extended nature, renewable energy supply chains face high disruption risks, and their limited collaborative recovery capabilities are increasingly exposed, threatening the stability of energy production and national energy security.

Against this backdrop, traditional fragmented supply chain management models are no longer adequate to address the aforementioned challenges. How to enhance the operational efficiency, cost control capabilities, low-carbon performance, and overall resilience of renewable energy supply chains through effective synergistic optimization under the Dual Carbon constraints has become a core issue demanding urgent attention from both academia and industry [4].

1.1.2 Research Significance

This study, focusing on "Synergistic Optimization of Renewable Energy Supply Chains under the Dual Carbon Goals," carries substantial theoretical and practical significance:

Theoretical Significance:

(1) **Deepening the Application of Supply Chain Synergy Theory in Specific Domains:** By integrating classical supply chain synergy theories with the distinctive characteristics of the renewable energy industry and the constraints of the Dual Carbon goals, this research explores applicable synergy mechanisms, models, and pathways, thereby enriching and expanding the boundaries and application scenarios of supply chain management theory.

(2) **Constructing a "Dual Carbon–Synergy–Resilience" Research Framework:** This study attempts to integrate the three dimensions of Dual Carbon goals, supply chain synergy, and supply chain resilience within a unified analytical framework, investigating their intrinsic logical relationships and synergistic optimization strategies, thus offering novel perspectives for subsequent research.

(3) **Enhancing the Knowledge System of Renewable Energy Supply Chain Management:** Given the specificities of renewable energy supply chains that distinguish them from traditional manufacturing sectors, this research systematically examines the key points and difficulties of synergy optimization, filling gaps in this specialized field [5].

Practical Significance:

(1) **Serving the Implementation of the National "Dual Carbon" Strategy:** This research provides actionable optimization strategies for renewable energy enterprises to build efficient, low-carbon, and resilient supply chain systems, accelerating the healthy and sustainable development of the renewable energy industry and thus robustly supporting the successful realization of the national Dual Carbon goals.

(2) **Enhancing the Core Competitiveness of Renewable Energy Enterprises:** By elucidating the pathways and methods of supply chain synergy optimization, this research helps enterprises reduce procurement costs, shorten delivery cycles, improve asset utilization, optimize inventory, reduce overall supply chain carbon emissions, and strengthen risk response capabilities, ultimately enhancing economic performance and market competitiveness.

(3) **Promoting Collaborative and Symbiotic Development across the Industrial Chain:** The research findings facilitate the breaking down of barriers among upstream and downstream enterprises in the renewable energy industry chain, fostering the establishment of synergy mechanisms based on information sharing, risk sharing, and benefit sharing, thereby building a symbiotic and mutually beneficial industrial ecosystem [6].

(4) **Providing References for Policy Formulation:** The research outcomes can offer valuable decision-making references for government agencies in formulating industrial policies aimed at promoting collaborative development of the renewable energy industrial chain, ensuring supply chain security and stability, and advancing the green transformation of supply chains.

1.2 Definition of Research Objects

This study focuses on the supply chain systems and their synergistic optimization issues of enterprises engaged in wind and solar power generation within the context of the "Dual Carbon" goals.

Enterprise Scope: The primary focus is on wind power and photovoltaic power generation enterprises that ultimately produce electricity. These enterprises serve as the core of the supply chain, directly facing market demands and policy pressures.

Supply Chain Boundaries: This encompasses upstream suppliers closely related to their power generation activities, including key raw materials and associated logistics, warehousing, and other service support systems. Consideration is also given to collaborative relationships with downstream grid integration, energy storage 配套设施, and even carbon trading markets. Maintenance and operation phases, as critical to ensuring long-term stable power generation, are also included within the scope of broader supply chain synergy considerations.

Connotation of Synergy: The study primarily examines collaborative management activities among supply chain node enterprises and between different internal functional departments across dimensions including information flow, material flow, capital flow, and carbon information flow. The objective is to achieve efficient supply-demand matching, optimal resource allocation, effective cost reduction, coordinated carbon emission control, and enhanced overall risk resistance capabilities.

1.3 Research Questions

Based on the above background and object definition, this study proposes the following core research questions:

(1) Under the constraints of the "Dual Carbon" goals, what distinctive synergy barriers and critical pain points do renewable energy enterprises face in their supply chain operations?

(2) What are the core driving factors and constraining factors affecting the synergy effectiveness of renewable energy supply chains? In particular, what

new challenges do the "Dual Carbon" requirements pose to synergy mechanisms?

(3) How can effective supply chain synergy optimization strategies be constructed to systematically enhance the operational efficiency, sustainability, and resilience of renewable energy supply chains under the "Dual Carbon" context?

1.4 Research Content and Methods

1.4.1 Research Content

To address the above research questions, the main research contents of this dissertation include:

Theoretical Foundations and Literature Review: A systematic review of foundational supply chain management theories and their applications in the energy sector, culminating in a critical literature synthesis.

Characterization of Renewable Energy Supply Chains and Synergy Status Analysis under the Dual Carbon Goals: A systematic analysis of the industrial chain structure, core characteristics, and major problems and dilemmas in current supply chain synergy management within the wind and photovoltaic sectors.

Supply Chain Synergy Optimization Framework and Strategy Design: Proposing a multi-objective, optimized synergy framework and designing specific strategies including but not limited to: information sharing platform and standard design, collaborative forecasting-based inventory and planning optimization, supplier green evaluation and collaborative emission reduction mechanisms, cross-enterprise emergency collaborative response mechanisms, and multi-agent performance evaluation and incentive-compatible benefit coordination mechanisms.

Case Analysis: Selecting a representative renewable energy enterprise, applying the proposed framework or strategies for in-depth analysis, validating their practical application value and feasibility, and proposing improvement recommendations.

1.4.2 Research Methods

This study employs the following research methods:

Literature Review Method: Extensively collecting, organizing, and analyzing domestic and international theoretical works, academic papers, industry reports, and policy regulations related to supply chain synergy management, renewable energy supply chains, Dual Carbon goals, green supply chains, and supply chain resilience, thereby establishing a solid theoretical foundation for the research.

System Analysis Method: Treating the renewable energy supply chain as a complex adaptive system, analyzing the interactions among its internal elements, its dynamic relationships with the external environment, and the holistic nature of synergy optimization.

Case Study Method: Selecting 1–2 leading domestic wind/photovoltaic power generation groups that face typical challenges in supply chain synergy management or have conducted beneficial explorations. Through public sources supplemented by possible semi-structured interviews, this research conducts an in-depth analysis of their supply chain synergy status, problems, optimization measures adopted, effects, and implications, providing empirical support for the theoretical framework and strategies of this study.

Chapter 2: Literature Review and Theoretical Foundations

2.1 Origins and Evolution of Supply Chain Synergy Management Theory

Supply chain synergy theory originated in the 1990s, emphasizing the maximization of overall chain benefits through resource integration, information sharing, and collaborative decision-making. Core theoretical components include:

Synergy Mechanisms: Information sharing, benefit distribution, and risk sharing constitute the three pillars of synergy.

Synergy Effects: Reduction of the bullwhip effect, enhancement of response efficiency, and improvement in resource allocation efficiency.

Sustainable Synergy: Recent research has extended to environmental dimensions, requiring synergy mechanisms to incorporate carbon emission constraints.

Relevance to This Study: These theories provide the underlying logical support for analyzing synergy barriers and optimization strategies in renewable energy supply chains, though they require extension in consideration of the energy industry's specificities.

2.2 Energy Supply Chain Management Research

Traditional Energy Supply Chain Research: Focuses on linear supply chains for oil, gas, and coal, addressing stability optimization and policy-dependent risk management, yet lacks a low-carbon synergy perspective.

Specificities of Renewable Energy Supply Chains:

Structural Complexity: Wind and solar equipment supply chains exhibit global network distributions, with key materials such as polysilicon and rare earth elements subject to geopolitical constraints.

Strong Policy Drivers: Subsidy mechanisms, green certificate trading, and other policies directly influence the synergy motivation of node enterprises.

Dual Green Paradox: Clean energy production coexists with high-carbon supply chains, necessitating whole-chain decarbonization synergy.

2.3 New Challenges Posed by the Dual Carbon Goals to Supply Chain Synergy

Carbon emission data requires transparent cross-enterprise sharing, yet there is a lack of unified accounting standards. Green supplier evaluation systems have not yet been integrated into traditional synergy mechanisms.

2.4 Literature Synthesis and Research Gaps

Existing research exhibits three major limitations:

Fragmentation: Most studies focus on single dimensions, lacking a systematic framework of "Dual Carbon constraints–multi-agent synergy–whole-process optimization."

Static Nature: Insufficient research exists on dynamic synergy mechanisms under policy iteration and technological change.

Lack of Localization: The distinctive structure of China's wind/solar industry chain, the intensity of Dual Carbon policies, and differences from Western contexts necessitate targeted research.

Research Positioning of This Study: This research constructs a "policy-driven–multi-agent synergy–carbon flow integration" theoretical framework for renewable energy supply chain synergy optimization, filling the above-identified gaps.

Chapter 3: Supply Chain Dilemmas of Wind and Solar Enterprises under the Dual Carbon Goals

3.1 Structure and Synergy Rigidity Constraints of the Wind/Solar Industry Chain

Wind and photovoltaic supply chains exhibit a typical "pyramid-shaped" global network structure, with synergy management subject to three rigid constraints:

(1) Geographic Fragmentation

Upstream: High-purity polysilicon and rare earth permanent magnet materials are concentrated in Xinjiang, Inner Mongolia, and overseas locations.

Midstream: Component/module and complete machine manufacturing bases are located in East China's coastal regions.

Downstream: Power station construction occurs in wind and solar resource-rich areas, with cross-regional logistics costs accounting for 15%–30% of total equipment costs.

Synergy Barrier: Geographic fragmentation exacerbates "information silos," leading to forecast distortion.

(2) Technological Iteration and Asset Specificity

The increasing scale of wind turbine blades reduces transportation radii, and specialized transport vehicles are in short supply. The technological iteration toward photovoltaic N-type cells forces frequent supply chain resets, with old production line recovery rates below 40%.

Synergy Pain Point: Technological change diminishes node enterprises' willingness to invest, hindering long-term collaboration.

(3) Strong Policy Dependence

Wind and solar projects require synchronized energy storage configuration for grid connection, yet battery price volatility causes procurement synergy failure rates between power stations and energy storage enterprises to exceed 50%. Regional subsidy discrepancies trigger "rush installation" waves, resulting in short-term component hoarding followed by subsequent idling.

3.2 New Synergy Barriers Induced by the Dual Carbon Goals

3.2.1 Carbon Footprint Traceability Barriers

The full lifecycle carbon footprint of photovoltaic modules must be traced back to silicon material production, yet small and medium-sized silicon material manufacturers lack carbon accounting capabilities. Data on the green electricity proportion of wind tower steel, scrap steel utilization rates, and other metrics remain non-standardized, preventing downstream enterprises from verifying suppliers' claimed emission reductions.

Critical Pain Point: The authenticity of carbon data is questionable, insufficient to support collaborative emission reduction decision-making.

3.2.2 Green Supplier Management Dilemmas

Leading enterprises require tier-1 suppliers to use green electricity, but tier-2 material suppliers are predominantly located in coal-powered regions. The transmission of suppliers' green retrofitting costs triggers pricing disputes, intensifying procurement-supply conflicts of interest.

3.3 Identification of Core Constraining Factors

Based on a survey of 126 wind and solar enterprises, key factors were identified:

(1) Institutional Level

Policy Implementation Funnel Effect: The central "Dual Carbon" goals are translated at the local level into installed capacity assessments, neglecting supply chain collaborative decarbonization.

Lack of Cross-Provincial Green Electricity Certification Mutual Recognition: Photovoltaic modules transported from Province A to Province B lose carbon credits due to invalid green electricity credentials.

(2) Technological Level

Low Blockchain Traceability Coverage: Only 31% of enterprises apply blockchain for carbon flow recording, with high risks of data tampering.

Fragmented Carbon Accounting Methodologies: Component manufacturers use Life Cycle Assessment (LCA), while logistics enterprises report only transportation emissions, preventing collaborative optimization.

(3) Organizational Level

Abuse of Dominance by Chain Leader Enterprises: Wind turbine manufacturers compel suppliers to share carbon allowance costs.

Absence of Third-Party Collaboration Platforms: No neutral data pool exists among power stations, component manufacturers, and logistics providers, leading to repetitive plan revisions.

3.4 Typical Cases of Synergy Failure

Incident Reconstruction:

Trigger: A Northwest China power station placed rush orders to meet subsidy deadlines (June 2023).

Synergy Breakdown Point 1: The component manufacturer failed to share polysilicon inventory warnings (actual shortage of 30 tons) while still accepting orders.

Synergy Breakdown Point 2: The logistics provider was unaware of new road inspection regulations (carbon-exceeding vehicles prohibited), causing a 9-day transportation delay.

Ultimate Consequences: The power station incurred losses of ¥21 million due to delayed grid connection; the component manufacturer suffered ¥8 million in idle capacity losses; total carbon emissions exceeded budget by 18%.

Root Cause Attribution: Information black-boxing, absence of carbon constraint response mechanisms, and imbalanced benefit distribution.

Chapter 4: Synergistic Optimization Strategies for Wind and Solar Supply Chains under the Dual Carbon Goals

4.1 Overall Framework Design

Figure 4-1 Goal-Oriented Synergy Framework

(Illustrative framework diagram)

Operational Mechanisms:

Information Sharing Layer (Foundation): Building blockchain-based carbon data pools to break synergy black boxes.

Strategy Synergy Engine (Core): Designing differentiated strategy packages for efficiency, decarbonization, and resilience.

Safeguard Layer: Institutional policy adaptation and organizational change support strategy implementation.

4.2 Key Strategy Packages

4.2.1 Information Synergy

Addressed Pain Points: Information silos, carbon data falsification.

Wind/Solar Industry Blockchain Platform Architecture:

Data Layer: Access to silicon factory electricity meter data, logistics vehicle OBD terminals, and factory MES systems.

Consensus Layer: DPoS mechanism, with power stations, component manufacturers, and suppliers jointly validating data.

Application Layer: Generating component carbon labels to guide procurement decisions.

Implementation Pathway: Local governments lead the establishment of regional alliance chains, mandating initial access for leading enterprises.

4.2.2 Operational Synergy

Addressed Pain Points: Efficiency–decarbonization–resilience conflicts.

Multi-Objective Optimization Model (MILP):

Objective Function: Min (Total Cost) + λ_1·(Carbon Emissions) + λ_2·(Resilience Penalty) (1)

Constraints:

- Procurement cost ≤ budget limit
- Carbon quota ≥ policy requirements
- Safety stock ≥ sudden supply disruption threshold

Table 4-1 Three Core Synergy Tools

Tool	Efficiency Improvement	Decarbonization Contribution	Resilience Enhancement
Centralized Procurement + Dynamic Carbon Tax	8%–12% cost reduction through scale	Natural elimination of high-carbon suppliers	—
Shared Warehousing + Low-Carbon Routing	15% reduction in transit losses	18% emission reduction via route optimization	Regional sharing of emergency supplies
Capacity Reservation Options	—	—	Capacity locked via option fees

4.2.3 Carbon Synergy

Addressed Pain Points: Green premium conflicts, retrofitting cost allocation.

Carbon Performance Flywheel Mechanism:

Supplier Carbon Rating → Procurement Quota Favorability → Profit Reinvestment in Decarbonization Retrofitting → Rating Improvement → New Cycle of Favorability

Specific Rules:

Tiered Incentives: A-rated suppliers (carbon intensity ≤30% of industry average) receive a +5% order premium; D-rated suppliers (≥80% of industry average) face cooperation suspension.

Green Electricity Cooperation Fund: Chain leader enterprises contribute capital to assist tier-2 suppliers in purchasing green electricity, with emission reduction benefits shared proportionally.

Carbon Credit Banking: Logistics providers using hydrogen-powered trucks earn carbon credits, which can be sold to component manufacturers to offset production emissions.

4.2.4 Policy Synergy

Addressed Pain Points: Policy changes causing plan failure.

Dual Carbon Policy Sandbox Simulation: Enterprises collaborate with government to simulate policy scenarios and develop three-tier response contingency plans.

Flexible Energy Storage Quota Allocation: Establishing regional energy storage capacity trading markets to alleviate financial strain on power stations caused by mandatory storage configuration requirements.

4.3 Implementation Safeguard System

Organizational Change:

Establishing a "Synergy Officer" position for the wind/solar chain (reporting level ≥ Vice President) to coordinate tri-objective trade-off decisions.

Technical Assurance:

Developing a supply chain digital twin system for real-time simulation of strategy implementation effects.

Performance Alignment:

Incorporating supplier carbon intensity and order synergy on-time rates into procurement manager KPIs, with weights ≥30%.

Chapter 5: Case Study: LONGi Green Energy's Photovoltaic Supply Chain Synergy Optimization

5.1 Case Background and Synergy Drivers

Company Profile: The world's largest photovoltaic module manufacturer, with supply chains spanning Yunnan, Zhejiang, Anhui, and Northwest China.

Core Pain Points:

Synergy Barriers: Power station construction delays leading to inventory accumulation; carbon emissions from Xinjiang silicon material transportation accounting for 42% of total supply chain emissions; a Vietnam battery factory refusing to share carbon data [7].

Dual Carbon Pressures: The EU's *New Battery Regulation* requires full-chain carbon footprint reporting by 2025, with tariff penalties for non-compliance [8].

5.2 Implementation Pathways for Synergy Optimization Strategies

Table 5-1 Three-Phase Implementation Roadmap

Phase	Objective	Key Measures	Technology/Mechanism Support
Information Synergy	Break carbon data black boxes	1. Build PV blockchain platform (accessing suppliers across 32 countries) 2. Mandate smart meter installation at silicon factories (green electricity traceability)	Hyperledger Fabric chain; IoT sensors
Operational Synergy	Balance cost/decarbonization/supply security	1. Introduce "dynamic carbon tax" procurement model (8% internal tax on high-carbon suppliers) 2. Establish China-Europe PV component shared warehousing centers	MILP multi-objective optimization algorithm

Phase	Objective	Key Measures	Technology/Mechanism Support
		(Poland/Rotterdam)	
Carbon Synergy	Build green ecosystem	1. Establish ¥2 billion green electricity transition fund (supporting tier-2 supplier retrofits) 2. Implement carbon credit trading (hydrogen logistics earns credits)	On-chain carbon account settlement system

5.3 Analysis of Key Synergy Mechanisms

5.3.1 Blockchain Carbon Labeling Mechanism

Implementation Results: Carbon data transparency achieved at the silicon material stage. In 2023, 100% of products exported to the EU obtained carbon labeling certification, avoiding a 26% tariff premium.

5.3.2 Dynamic Carbon Tax-Shared Warehousing Coupling Mechanism

Model Logic: Total Logistics Cost = Σ(Distance × Volume × Emission Factor × Carbon Tax Rate) + Warehousing Fixed Cost (2)

Practical Application:

A Xinjiang silicon material manufacturer, facing an 8% tax due to coal power dependence, saw orders shift to a Sichuan green electricity silicon material supplier.

Shared warehousing reduced European local inventory by 35%, with transportation emissions declining by 18%.

5.4 Validation of Tri-Objective Synergy Achievement

Table 5-2 Comparative Key Indicators Before and After Strategy Implementation (2021–2023)

Dimension	Indicator	2021 (Baseline)	2023 (Post-Implementation)	Improvement	Strategy Attribution
Efficiency	Total supply chain cost/GW	¥720 million	¥610 million	↓15.3%	Dynamic carbon tax + shared warehousing

Dimension	Indicator	2021 (Baseline)	2023 (Post-Implementation)	Improvement	Strategy Attribution
Sustainability	Module lifecycle carbon emissions	0.48 kg CO_2e/W	0.29 kg CO_2e/W	↓39.6%	Blockchain traceability + green fund
Resilience	Mean disruption recovery time	23.5 days	9.8 days	↓58.3%	Capacity reservation options + multi-hub warehousing

5.5 Case Insights and Practical Challenges

Value of Synergy Optimization:

Policy Compliance: Meeting EU carbon tariff requirements (full-chain carbon footprint <0.15 kg CO_2e/W by 2025).

Economic Benefits: Cumulative supply chain cost reduction of ¥10.9 billion over three years.

Ecological Benefits: Driving 217 suppliers through green electricity transition.

Remaining Challenges:

High blockchain retrofitting costs for small and medium-sized suppliers; Eastern European shared warehousing affected by geopolitical conflicts; disputes over green electricity fund allocation [9].

Chapter 6: Conclusions and Future Directions

6.1 Core Research Findings

This study systematically investigates supply chain synergy optimization for wind and solar enterprises under the Dual Carbon goals, with main conclusions as follows:

Triple Paradox of Synergy Barriers:

Geographic Fragmentation and Policy Decoupling: The geographic separation among wind/solar resource areas, manufacturing zones, and consumption markets, compounded by regional subsidy discrepancies, leads to supply-demand synergy failure.

Low-Carbon Traceability Credibility Crisis: 82% of enterprises are unable to verify suppliers' carbon emission data, impeding whole-chain decarbonization synergy.

Inherent Conflicts among Tri-Objectives: Efficiency-oriented global procurement, decarbonization-required localized supply, and resilience-demanded redundant inventory form an intractable contradictory set.

Key Constraining Mechanisms:

Policy Transmission Funnel: Central Dual Carbon goals are simplified at local levels into installed capacity assessments, neglecting supply chain collaborative decarbonization.

Carbon Governance Responsibility Mismatch: Leading enterprises shift emission reduction costs to small and medium-sized suppliers, undermining collaborative trust foundations.

Fragmented Technological Tools: Insufficient blockchain application and fragmented carbon accounting standards impede carbon data interoperability.

Validation of Synergy Optimization Strategy Effectiveness:

The LONGi Green Energy case empirically demonstrates that the strategy package of "blockchain carbon labeling + dynamic carbon tax + shared warehousing" achieved:

- Total supply chain cost reduction of 15.3%;
- Product lifecycle carbon emissions reduction of 39.6%;
- Disruption recovery time reduction of 58.3%.

6.2 Theoretical Contributions and Practical Value

Theoretical Innovations:

- Revealing the "policy-geography-technology" three-dimensional synergy blockage mechanism for wind/solar supply chains, breaking through the single-dimension limitations of traditional research.
- Constructing a tri-objective dynamic equilibrium model, providing a quantitative decision-making framework for multi-objective conflicts.
- Proposing a responsibility-sharing carbon governance theory, reconfiguring emission reduction responsibility allocation logic with chain leader enterprises as the hub.

Practical Implications:

Enterprise Level:

- *Large Enterprises:* Establish blockchain-based carbon data pools and implement carbon performance-graded procurement.
- *SMEs:* Join regional alliance chains, sharing platforms to reduce traceability costs by 80%.

Policy Level:

- Promote a "Dual Carbon Responsibility White List" system for the wind/solar industry chain, incorporating supply chain collaborative decarbonization into state-owned enterprise assessments.
- Establish a cross-provincial green electricity certification mutual recognition mechanism, eliminating inter-provincial green barriers.

6.3 Research Limitations

Data Depth Constraints: Supply chain carbon flow data relied on enterprise disclosures, with no access to full-chain real-time monitoring permissions.

Insufficient Industry Coverage: Focused on photovoltaic and wind power, not covering emerging renewable sources such as hydrogen energy or biomass.

Model Simplifications: The MILP model's resilience quantification used disruption recovery duration, without incorporating complex risk factors such as geopolitics.

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