



The Mechanism and Coupling Measurement of Intelligent Digital Technology Empowering the Green and Low-Carbon Transition of the Energy Industry

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Abstract: Against the backdrop of the global carbon neutrality initiative and China's "Dual Carbon" strategy, the green and low-carbon transition of the energy industry serves as the core lever for realizing sustainable economic and social development. Intelligent digital technologies represented by artificial intelligence, digital twins, the Internet of Things (IoT), and blockchain have become critical engines driving improvements in energy efficiency and industrial transformation and upgrading. This paper systematically reviews core research outcomes over the past decade worldwide regarding intelligent digital technologies and green energy transition, and constructs an analytical framework spanning four dimensions: technical foundations and application scenarios, functional transmission mechanisms, coupling coordination measurement, and practical transition pathways. It comprehensively interprets the internal logic and research progress of intelligent digital technologies enabling the green transition of the energy industry. The study finds that existing literature has verified three pathways through which intelligent digital technologies advance cost reduction and efficiency gains in the energy sector: optimizing factor allocation, boosting full-chain energy efficiency, and reconstructing industrial value chains. Nevertheless, prevailing research is dominated by a unidirectional empowerment perspective, lacks thorough elaboration on bidirectional coupling mechanisms, insufficiently explores regional industrial heterogeneity, and neglects transition pathways for micro, small, and medium-sized enterprises (MSMEs). Accordingly, this paper further discusses consensus and limitations within current scholarship, and proposes future research directions covering four dimensions: deepening bidirectional coupling mechanisms, designing differentiated regional pathways, exploring the evolutionary behaviors of micro entities, and building a multi-policy coordination system. It provides systematic references for theoretical research and practical advancement of the coordinated digital and green development of the energy industry.

Keywords: Intelligent Digital Technology; Green Energy Transition; Coupling Coordination Degree; Dual Carbon Targets; Green Total Factor Productivity

1. Introduction

The global climate governance system is undergoing accelerated restructuring, and carbon neutrality has become a long-term development strategy for most nations. The clean, low-carbon, and intelligent transformation of energy systems constitutes the core domain for achieving emission reduction targets (Chu et al., 2017; Gielen et al., 2019). From a long-cycle perspective on energy system evolution, humanity's energy utilization is shifting from fossil fuels to renewable energy and from high-carbon to low-carbon modes, and carbon neutrality strategies represent an inevitable choice aligned with this evolutionary law (Caineng et al., 2022). International energy research confirms that large-scale deployment of renewable energy and sustained improvements in energy utilization efficiency are the two pillars of the global net-zero emission target by 2050. In-depth penetration of intelligent digital technologies is reshaping the full-process paradigms of energy production, transmission, consumption, and storage, delivering technical support for efficient, flexible, and secure operation of energy systems (Breyer et al., 2022; Kober et al., 2020).

From China's practical perspective, the "Dual Carbon" goals and the construction of new power systems impose higher requirements on quality, efficiency, and momentum transformation within the energy industry. Traditional energy sectors face prominent bottlenecks including high pressure on renewable energy accommodation, elevated equipment operation and maintenance costs, diminishing marginal returns on energy efficiency improvement, and inadequate industrial chain coordination. Pure hardware technology upgrades can no longer meet the demands of high-quality

development (Liu et al., 2023; Zhang et al., 2025). Meanwhile, deep integration between the digital economy and the real economy has driven intelligent digital technologies such as big data, artificial intelligence, and industrial internet to penetrate the energy sector, fostering new business forms including smart power stations, virtual power plants, digital twin power grids, and integrated energy services that demonstrate remarkable decarbonization and efficiency improvement potential (Inderwildi et al., 2020; Gao et al., 2025). Under this context, clarifying the internal mechanisms through which intelligent digital technologies drive the green transition of the energy industry, measuring the level of coupling coordination between the two systems, and exploring transition pathways adaptable to diverse regions and entities have emerged as core research topics attracting shared attention from academia and industry.

Extant research has accumulated abundant findings on the energy applications of intelligent digital technologies, energy efficiency enhancement, and industrial green transition. Technological studies validate the practical value of artificial intelligence and IoT in scenarios such as power generation forecasting, fault diagnosis, and load scheduling (Hamdan et al., 2024; Kiasari et al., 2024). Industrial-level empirical analyses confirm the positive driving effect of digital transformation on green total factor productivity (Hao et al., 2023; Jing et al., 2025). Regional scholarship further discusses the spatial heterogeneity of energy digitalization (Pang et al., 2025). Overall, however, existing literature suffers from three primary deficiencies: first, most studies focus on the unidirectional empowerment of energy transition by intelligent digital technologies, with

insufficient attention to bidirectional coupling mechanisms through which energy efficiency gains and green demand in turn drive iterative technological upgrades; second, measurement systems rely heavily on generalized indicators with poor adaptability for regions dominated by private industrial clusters and MSMEs; third, transition pathways tend to prioritize macro policy design, while actionable solutions for segmented scenarios and micro entities remain underdeveloped.

Against this backdrop, this paper systematically integrates classical and cutting-edge global research on intelligent digital technologies and green energy transition, and conducts a comprehensive literature review following the logical thread of “technical foundations – functional mechanisms – coupling measurement – practical pathways”. It sorts core consensus and academic advances in this field, dissects limitations and research gaps in current scholarship, and proposes directions for future inquiry, so as to deliver systematic references for theoretical research and policy formulation targeting coordinated digital and green development of the energy industry.

2. Technical System and Application Scenarios of Intelligent Digital Technologies Empowering Green Energy Transition

Intelligent digital technologies represent an integrated collective of digital and intelligent technologies centered on data as a core production factor and algorithms as a core driving force, encompassing technical clusters including artificial intelligence, digital twins, industrial IoT, and blockchain, which collectively form the technical foundation for the green transition of the energy industry (Aldoseri et al., 2024;

Fraga-Lamas et al., 2021). Each category of technology performs differentiated functions across distinct links of energy systems, forming a full-chain technical application framework covering power generation, power grids, end-user loads, and energy storage.

2.1 Functional Positioning of Core Technical Clusters

2.1.1 Artificial Intelligence: The Core Engine for Intelligent Decision-Making of Energy Systems

Through machine learning and deep learning algorithms, artificial intelligence excavates and analyzes massive energy data to realize forecasting, optimization, and decision-making for energy production and consumption, serving as the core technology for improving operational efficiency and cutting maintenance costs of energy systems (Gao et al., 2025; Yao et al., 2023). In renewable power generation, artificial intelligence enables high-precision forecasting of wind and solar output based on meteorological data, mitigating grid shocks caused by intermittent new energy sources. In equipment operation and maintenance, AI fault diagnosis algorithms identify hidden equipment hazards in advance, shifting post-facto maintenance to predictive maintenance and significantly lifting equipment utilization rates and service lifespans (Hamdan et al., 2024; Ukoba et al., 2024).

Additionally, artificial intelligence is widely deployed in scenarios including energy system optimal scheduling, demand response, and carbon footprint accounting, acting as the pivotal support for upgrading energy systems from automation to intelligence (Fan et al., 2023; Chen et al., 2021). From a techno-economic evaluation perspective, artificial intelligence also delivers efficient tools for cost-benefit analysis of energy efficiency upgrades and renewable energy technologies,

enhancing the scientific rigor and precision of project decision-making (Chen et al., 2021).

2.1.2 Digital Twins: The Key Carrier for Virtual-Physical Interaction of Energy Systems

Digital twin technology constructs virtual mirrors corresponding one-to-one with physical energy systems to realize real-time mapping, simulation, and iterative optimization across the full lifecycle, providing visual and deducible technical tools for refined control of energy systems (Steindl et al., 2020; Wang & Ma, 2024). Steindl et al. (2020) proposed a general digital twin architecture for industrial energy systems, clarifying core workflows of data collection, model construction, simulation optimization, and feedback control, which delivers a reference framework for deploying industrial digital twins.

At the equipment level, digital twins simulate operating conditions of wind turbines, photovoltaic modules, transformers, and other core power equipment to predict performance degradation and fault risks. At the system level, digital twin power grids simulate power flow distribution and fault evolution under diverse scenarios, supplying simulation support for power grid planning and emergency dispatching (Yang et al., 2022; Li et al., 2020). With improvements in modeling precision and computing power, digital twin technology is expanding from single equipment to park-level and city-level integrated energy systems, emerging as the core technical architecture integrating smart energy systems and smart cities (Wang & Ma, 2024). Meanwhile, network-based business models built on digital twin platforms are gradually emerging, delivering new carriers for service-oriented transformation of energy enterprises (Li et al., 2020).

2.1.3 Industrial IoT and Edge Computing: The Fundamental Network for Energy Data Collection and Processing

Industrial IoT deploys sensors and intelligent terminals to realize full-link perception and real-time collection of energy system data, while edge computing conducts preliminary data processing at the source. Together, they form the perceptual neural network underpinning energy digitalization (Fraga-Lamas et al., 2021; Rajagopalan et al., 2024). The integration of green IoT and edge AI further reduces energy consumption and latency of data processing, emerging as a critical enabling technology for circular economy and smart energy development within the context of Industry 5.0 (Fraga-Lamas et al., 2021).

In industrial scenarios, IoT technology realizes itemized metering and refined management of energy consumption for production equipment, identifying invalid energy consumption links. In building scenarios, smart home and building automation systems leverage IoT to dynamically adjust energy consumption, boosting building energy efficiency (Metallidou et al., 2020; Bibri & Krogstie, 2020). Within distribution networks, coordinated deployment of IoT and cloud computing enables real-time monitoring, intelligent maintenance, and efficient scheduling of distribution grids, substantially elevating sustainability and operational efficiency of distribution systems (Rajagopalan et al., 2024).

2.1.4 Blockchain: Technical Support for Distributed Energy Trading and Trust Construction

Leveraging decentralized, tamper-proof, and traceable technical characteristics, blockchain delivers trust mechanisms for distributed energy trading, green certificate and carbon credit traceability, energy finance, and

other scenarios, constituting a vital technical pathway for resolving coordination challenges in distributed energy systems (Ahl et al., 2019; Wu & Tran, 2018). Early scholarship systematically sorted application scenarios of blockchain in sustainable energy systems, covering peer-to-peer transactions, green electricity traceability, demand response, and energy finance (Wu & Tran, 2018).

In distributed power generation, blockchain-based peer-to-peer energy trading enables mutual surplus power exchange among users, raising the local accommodation rate of distributed renewable energy. In green electricity certification, blockchain realizes full-chain traceability of green power production, transmission, and consumption, guaranteeing authenticity and transparency of green electricity transactions (Teufel et al., 2019; Lv, 2023). Nevertheless, blockchain deployment in the energy sector faces multiple constraints including technical performance, regulatory frameworks, and business models. Interconnections and constraints across technical, economic, social, environmental, and institutional dimensions represent core challenges requiring resolution for large-scale commercialization (Ahl et al., 2022).

2.2 Core Application Scenarios of the Energy Industry

2.2.1 Power Generation Side: Efficient Development and Intelligent Operation of Clean Energy

Large-scale exploitation of renewable energy constitutes the core component of energy transition, and intelligent digital technologies markedly enhance development efficiency and operational stability of wind, solar, hydro, and other clean energy sources (Blaabjerg et al., 2023; Tang et al., 2021). Power electronics technology provides hardware foundations for grid

integration of large-scale renewable energy, while artificial intelligence and digital twins optimize full workflows of power station design, construction, and operation and maintenance from a software perspective (Huang, 2019; Zhang et al., 2018). For instance, offshore wind farms utilize digital twins to simulate wind turbine performance under diverse sea conditions, paired with meteorological AI forecasting to optimize power generation scheduling and substantially boost equipment utilization hours. Photovoltaic power stations deploy drone inspections and AI image recognition to rapidly locate module faults, cutting labor costs for operation and maintenance (Hamdan et al., 2024).

Intelligent digital technologies also play a pivotal role in emerging clean energy sectors such as hydrogen energy. Efficiency improvements in electrolytic water hydrogen production and CO₂ catalytic conversion rely heavily on breakthroughs in catalyst material research, while the integration of artificial intelligence and automated experimental platforms drastically accelerates screening and R&D of new materials, driving cost declines for green hydrogen and electrofuel technologies (Tabor et al., 2018; Gong et al., 2019; Zheng et al., 2018). Research on catalyst and electrode materials has advanced the development of two-dimensional materials and single-atom catalysts to lift energy conversion efficiency, while plasma synthesis and doping modification further optimize catalytic performance (Lin et al., 2020; Khan et al., 2019; Dou et al., 2018). Meanwhile, resource utilization technologies for electronic waste recycled materials as catalysts open new avenues for integrating energy technology and circular economy (Seif et al., 2024). Additionally, breakthroughs in mechanical intelligent energy harvesting

and wireless power transfer diversify pathways for acquiring and utilizing distributed energy (Zhao et al., 2023; Zhang et al., 2018).

Intelligent control systems dynamically adjust hydrogen production loads according to variable renewable energy output, enabling efficient coordinated operation of integrated wind-solar-hydrogen systems (Gao et al., 2024; Brauns & Turek, 2020). Multi-energy complementary hydrogen systems integrate full chains of renewable power generation, hydrogen production, hydrogen storage, and hydrogen consumption, evolving into a key development direction for regional clean energy systems (Li et al., 2020). Beyond hydrogen production, electrocatalytic CO₂ reduction and CO₂ hydrogenation to methanol deliver technical pathways for constructing zero-carbon energy networks, with continuous advances in catalyst research lifting conversion efficiency (Li et al., 2022; Etim et al., 2020). Industrial high-current scenarios have also witnessed breakthroughs in technologies including biomass electrochemical upgrading coupled with hydrogen production and 5-hydroxymethylfurfural electrooxidation, expanding application scenarios and economic viability of green hydrogen (Qian et al., 2023; Sun et al., 2022; Zhai et al., 2023).

2.2.2 Power Grid Side: Secure Stability and Flexible Scheduling of Smart Grids

Smart grids serve as the core carrier for accommodating high-proportion renewable energy. Intelligent digital technologies comprehensively upgrade perception, decision-making, and control capabilities of power grids, driving the evolution of traditional unidirectional transmission networks into new power systems featuring coordinated interaction between sources, grids, loads, and storage (Alotaibi et al., 2020;

Kabeyi & Olanrewaju, 2023). Extant literature systematically reviews smart grids from technical architecture, application scenarios, and development trend dimensions, verifying that integration of information communication technology and power technology represents the core characteristic of smart grids (Rehmani et al., 2018; Salkuti, 2022).

In power grid operation, wide-area measurement systems combined with AI algorithms enable rapid fault identification and self-healing control of power grids, lifting stability under high shares of new energy integration (Ourahou et al., 2020; Rehmani et al., 2018). In power dispatching, intelligent scheduling algorithms coordinate multi-resource systems of sources, grids, loads, and storage to balance maximum accommodation of renewable energy and economic grid operation (Kiasari et al., 2024; Salkuti, 2022). Integration of machine learning and energy storage systems further enhances grid regulation capacity for intermittent renewable energy, emerging as a core technical direction for future smart grids (Kiasari et al., 2024).

As extensions of smart grids, integrated energy distribution systems integrate distributed power sources, energy storage, diversified loads, and multi-energy flow networks, with research on core planning and operational issues delivering theoretical support for regional energy system optimization (Wang et al., 2018). Optimal planning technologies for AC-DC hybrid transmission systems provide solutions for grid upgrading under large-scale distributed energy integration (Liu et al., 2019).

Energy storage technologies constitute critical regulating resources for new power systems, and intelligent digital technologies optimize charge-discharge strategies and health

management of storage systems to boost utilization efficiency and service lifespans (Njema et al., 2024; Ma et al., 2021). Battery management systems paired with AI algorithms accurately estimate battery state of charge and state of health, optimizing charge-discharge curves. Virtual power plant technology aggregates scattered energy storage, loads, and distributed power sources to participate in grid peak shaving and frequency regulation, lifting system flexibility (Amici et al., 2022; Li et al., 2020). European research initiatives such as BATTERY 2030+ have formulated long-term roadmaps for battery technology evolution, clarifying development directions for energy storage technologies (Amici et al., 2022).

2.2.3 End-User Side: Demand Response and Integrated Energy Services

Intelligent digital technologies unlock adjustable potential on the end-user side, shifting energy consumption from passive acceptance to active participation and releasing sustained energy efficiency improvement space across industrial, building, and transportation sectors (Heffron et al., 2020). Industrial demand-side flexibility not only elevates grid regulation capacity but also represents a pivotal element for equitable energy transition and industrial green development (Heffron et al., 2020).

In industrial sectors, energy management systems integrate production data to optimize production schedules and energy consumption plans, enabling participation in power demand response while cutting corporate energy costs and delivering peak shaving resources for power grids. In building sectors, smart building systems coordinate air conditioning, lighting, elevators, and other energy-consuming equipment to dynamically adjust operational strategies based on

environmental parameters, sustaining improvements in building energy efficiency (Metallidou et al., 2020; Casini, 2018). Deployment of active dynamic windows and smart dimming glass further reduces heating, cooling, and lighting energy consumption in buildings, emerging as a core technical direction for energy-efficient construction (Casini, 2018; Tan et al., 2025). At the smart city scale, environment-data-driven smart solutions systematically elevate urban energy utilization efficiency and reduce pollution emissions (Bibri & Krogstie, 2020).

Simultaneously, new business forms of integrated energy services are developing rapidly, delivering efficiency gains for end-user energy consumption through multi-energy complementarity and coordinated optimization. Construction of energy internet and transactive energy systems breaks information barriers across energy varieties and market entities, realizing coordinated scheduling and market-oriented trading of cooling, heating, electricity, gas, and other energy carriers (Wu et al., 2021; Mishra & Singh, 2023). Transactive energy internet driven jointly by digitalization and decentralization is evolving into a vital form of future energy systems, with relatively mature research frameworks established for core technologies and infrastructure architectures (Wu et al., 2021).

Rise of local energy markets and energy communities further promotes local accommodation and shared utilization of distributed energy, emerging as a key direction for end-user energy transition (Lezama et al., 2018; Wu et al., 2022). Integration of microgrids and blockchain technology enables energy communities to transcend basic peer-to-peer trading toward collective, autonomous energy

communities, lifting self-consistency and resilience of community energy systems (Wu et al., 2022). Relevant research systematically sorts concepts, progress, and challenges of renewable energy communities, supplying references for large-scale deployment (Ahmed et al., 2024).

2.2.4 Cross-Sector Integration: Energy Coordination Across Transportation, Construction, and Agriculture

Intelligent digital technologies drive deep integration between energy systems and transportation, construction, agriculture, and other sectors, forming a new landscape of cross-sector coordinated decarbonization. In transportation, connected and intelligent vehicles paired with vehicle-grid interaction technology utilize electric vehicles as mobile energy storage units to participate in grid regulation, lifting renewable energy accommodation capacity. Deployment of privacy-preserving technologies such as federated learning further supports low-carbon upgrading of intelligent transportation systems, advancing climate protection and green development (Tan et al., 2025).

In construction, integration of building-integrated photovoltaics, smart windows, and energy storage transforms buildings from pure energy consumers into prosumers (Yang et al., 2022). Deployment of digital twin technology in intelligent green buildings realizes full-lifecycle energy consumption optimization and intelligent control, serving as core tools for building energy conservation and smart upgrading (Yang et al., 2022).

In agriculture, integration of smart agriculture and clean energy fosters new forms including agrivoltaics and intelligent irrigation, advancing clean and efficient energy utilization in agricultural production (Qin et al., 2022;

Hou et al., 2021). Digital technology and service-driven sustainable agricultural transformation has yielded abundant practical cases in China and the EU, verifying the positive impact of digitalization on agricultural energy efficiency and green development (Qin et al., 2022). Blockchain-enabled innovative ecosystem frameworks for clean energy in smart agriculture have constructed technology coupling mechanisms and development prospects, delivering new models for agricultural energy transition (Hou et al., 2021).

Furthermore, hard-to-abate sectors including shipping are exploring deployment of zero-carbon fuels such as green hydrogen, green ammonia, and methanol, with intelligent digital technologies supplying technical support for fuel production and marine power system optimization, emerging as critical pathways for rapid decarbonization of shipping (Shi et al., 2023). Integration of additive manufacturing and digitalization also advances intellectualization and lightweight design of energy equipment, further cutting energy consumption and carbon emissions during production (Tian et al., 2022).

3. Functional Mechanisms Through Which Intelligent Digital Technologies Drive the Green Transition of the Energy Industry

Driving the green transition of the energy industry via intelligent digital technologies does not rely on simple superposition of individual technologies. Instead, penetration of data production factors reconstructs allocation modes of production factors, optimizes full-chain operational efficiency, and reshapes industrial value chain division, forming multi-layered systematic functional mechanisms.

3.1 Production Factor Allocation Optimization Mechanism:

Empowering Effects of Data Production Factors

Within the digital economy, data has evolved into a new production factor alongside capital, labor, and energy. Intelligent digital technologies break allocation boundaries of traditional production factors through circulation, sharing, and reuse of data elements, realizing Pareto improvements in factor allocation efficiency (Litvinenko, 2020; Qu et al., 2025). Litvinenko (2020)'s research on mining sectors confirms that the digital economy constitutes a core driver of industrial technological upgrading, lifting total factor productivity by enhancing resource allocation efficiency and accelerating technology diffusion, a logic equally applicable to the energy industry.

On one hand, deep integration of data elements with capital, technology, labor, and other traditional factors amplifies production efficiency of each factor: integration of digital technologies and labor generates digital skill dividends to elevate worker productivity, while integration with technology accelerates technological iteration and diffusion to raise the pace of technological progress. On the other hand, non-competitive and replicable characteristics of data elements enable low-cost circulation across industrial chains, promoting cross-industry factor sharing and coordinated allocation while mitigating factor misallocation across the industrial chain (Jing et al., 2025).

Within the energy industry, allocation optimization effects of data elements are prominently reflected in energy resource scheduling and distribution. Energy big data platforms enable cross-regional and cross-entity sharing of energy supply-demand information, lifting spatial allocation efficiency of energy resources. Internal enterprises can optimize energy consumption timelines for production

workflows through integrated production and energy data, reducing energy consumption per unit output (Hao et al., 2023). Qu et al. (2025) further note that productivity gains from digital transformation are realized through synergistic integration of artificial intelligence, green technology, and energy technology, with coupling effects of the three exceeding independent effects of individual technologies.

3.2 Full-Chain Energy Efficiency Improvement Mechanism: Decarbonization Effects of Technological Empowerment

Through refined control, intelligent optimization, and predictive forecasting, intelligent digital technologies realize full-chain energy efficiency improvements across production, transmission, and consumption links of the energy industry, constituting the core transmission pathway driving green transition (Inderwildi et al., 2020; Liu et al., 2023). Inderwildi et al. (2020) systematically interpreted decarbonization mechanisms of intelligent cyber-physical systems for energy sectors, noting that closed loops of real-time perception, intelligent decision-making, and automatic control enable systematic decarbonization across full energy workflows, emerging as core technical pathways for energy decarbonization.

In production links, intelligent production scheduling systems dynamically adjust production plans according to product orders and energy prices, optimizing operational parameters of production equipment to cut energy consumption and carbon emissions while guaranteeing production capacity. In transmission links, line loss management and reactive power optimization technologies of smart grids reduce energy loss during power transmission, lifting energy delivery

efficiency. In consumption links, refined energy consumption monitoring and intelligent control systems identify and eliminate invalid energy consumption, boosting end-user energy utilization efficiency.

From a technological effect perspective, intelligent digital technologies not only elevate energy utilization efficiency but also accelerate green technological innovation. Digital transformation lowers trial-and-error costs for corporate R&D, raising efficiency and success rates of green technology research, which in turn sustains energy efficiency improvements via technological progress (Feng et al., 2022; Zheng & Zhang, 2023). Liu et al. (2023) systematically sorted pathways through which digital technologies drive carbon neutrality in China's energy sector, identifying three core channels for carbon emission reduction: lifting renewable energy shares, optimizing energy system operation, and cutting end-user energy consumption.

3.3 Industrial Value Chain Reconstruction Mechanism: Value-Added Effects of Coordinated Integration

Intelligent digital technologies drive the evolution of the energy industry from traditional linear value chains of “production – transmission – consumption” toward networked, service-oriented, platform-based value ecosystems, reshaping value distribution and division modes of the industry (Chen et al., 2021; Li et al., 2023). Chen et al. (2021)'s research revealed interactive relationships between business models and digital technologies during digital servitization, noting continuous interaction between the two constitutes core logic for corporate service-oriented transformation and value appreciation.

On one hand, platform-based models reduce coordination costs across

industrial chains. Industrial internet platforms connect upstream and downstream enterprises to realize coordinated linkage of R&D, production, and supply chains, lifting overall operational efficiency of industrial chains. Meanwhile, platforms aggregate digital transformation demands of MSMEs, lowering transformation thresholds for small enterprises via large-scale service provision (Li et al., 2023; Teng et al., 2022). Li et al. (2023) systematically elaborated theoretical mechanisms and business models through which industrial internet platforms empower digital transformation of MSMEs, delivering clear practical frameworks for platform-based upgrading.

On the other hand, digital servitization has emerged as a new value growth point for the energy industry. Leveraging digital capabilities, energy enterprises extend from pure energy product supply to value-added services including integrated energy services, energy-saving operation and maintenance, and digital solution provision, driving industrial upgrading toward high-end value chain segments (Chen et al., 2021). For example, new energy equipment manufacturers install intelligent sensing modules to deliver remote operation and maintenance and energy efficiency optimization services to clients, boosting customer stickiness while expanding revenue streams. Such value chain reconstruction not only elevates added value of the energy industry but also reduces full-lifecycle energy consumption and carbon emissions via service-oriented models, realizing win-win alignment of economic and environmental value.

3.4 Schematic Logical Text for Functional Mechanisms of Intelligent Digital Technologies Driving Green Energy Transition

To systematically visualize the

multi-layered transmission logic of the three core functional mechanisms through which intelligent digital technologies drive the green and low-carbon transition of the energy industry, as well as the bidirectional feedback

coupling relationship between digital empowerment and industrial green upgrading, this paper constructs a complete logical schematic diagram of the transmission pathways, as shown in Figure 1.

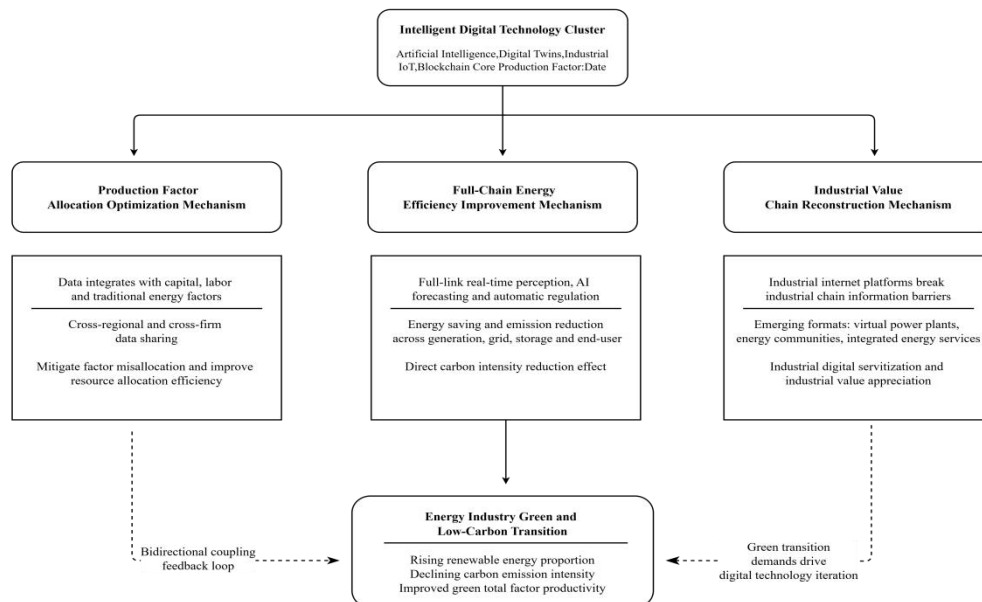


Figure 1. Logical Diagram of Mechanisms of Intelligent Digital Technology Empowering Energy Green Transition

4. Coupling Coordination Measurement and Evolution Characteristics of Digitalization and Greenization in the Energy Industry

With deepening research, scholars have gradually recognized that digitalization and greenization are not unidirectional driving relationships but mutually influential and mutually reinforcing bidirectional coupling systems. Constructing scientific measurement systems, quantifying coupling coordination levels between the two systems, and revealing their evolutionary laws constitute critical prerequisites for advancing coordinated development.

4.1 Methodology and Indicator Construction of Coupling Coordination Measurement

The coupling coordination degree model represents the mainstream tool for measuring interactive relationships

between multi-systems. Adopting a system theory perspective, it treats digitalization and greenization as two relatively independent yet interrelated subsystems, quantifying coordinated development levels by calculating coupling degree and coordination degree (Zhang et al., 2025; Fridgen et al., 2020). Fridgen et al. (2020)'s sectoral coupling theory delivers a holistic perspective for multi-system coupling research in energy sectors, noting that coupling coordination across distinct energy sectors and technical systems elevates overall system efficiency and facilitates realization of transition targets.

In constructing indicator systems, extant research generally establishes evaluation indicators for digitalization and greenization subsystems across input, output, and environmental dimensions. The digitalization subsystem typically selects indicators

including digital infrastructure levels, digital technology input intensity, digital talent ratios, and depth of data application. The greenization subsystem covers energy utilization efficiency, carbon emission intensity, renewable energy share, and green technological innovation capacity (Zhang et al., 2025; Liu et al., 2025). The entropy weight method dominates weight determination, leveraging discrete characteristics of raw data to assign indicator weights and avoid bias from subjective weighting.

Zhang et al. (2025) constructed an evaluation system for coupled and coordinated development of digitalization and greenization targeted at the energy industry, measuring digitalization levels across three dimensions: digital infrastructure, digital technology application, and digital innovation capacity, and measuring greenization levels across energy efficiency, emission reduction performance, and green transition potential. The study deployed the coupling coordination degree model to calculate coupling coordination grades of China's energy industry, verifying significant positive correlation between coupling coordination degree and industrial high-quality development, and proposing targeted improvement pathways accordingly.

4.2 Heterogeneous Characteristics of Coupled and Coordinated Development

Empirical research universally identifies prominent regional, industrial, and firm heterogeneity in coupling coordination levels between digitalization and greenization of the energy industry. Regionally, regions with advanced economic development, complete digital infrastructure, and solid industrial foundations exhibit higher coupling coordination degrees, with stronger empowering effects of digitalization on green transition. Less

developed regions face constraints of capital, technology, and talent that delay digital transformation, resulting in lower coupling levels (Pang et al., 2025; Liu et al., 2025). Pang et al. (2025)'s research on Sichuan Province found significant disparities in energy digital transformation across prefecture-level cities within the province. Central cities such as Chengdu lead in digital technology application and policy support, while resource-based cities suffer from insufficient transition momentum, based on which differentiated regional advancement pathways were proposed.

At the firm level, large energy enterprises leverage capital and talent advantages to conduct full-chain digital transformation, achieving deeper integration of digitalization and greenization. MSMEs universally face dilemmas of "unwillingness, incapacity, and insufficient funds for transformation", with digital transformation limited to basic office workflows that exert minimal impacts on production-side energy efficiency improvements (Teng et al., 2022; Liu et al., 2025). Liu et al. (2025)'s research on manufacturing enterprises identified threshold effects of corporate digital transformation on green low-carbon performance: digital input must cross a certain threshold to generate significant decarbonization and efficiency gains, a barrier most MSMEs fail to overcome.

Additionally, ownership structure and industrial technical attributes shape coupling outcomes. Regions with active private economies exhibit stronger market-driven momentum for corporate digital transformation yet face more severe resource constraints. High-energy-consuming industries possess greater energy efficiency improvement potential, yielding higher marginal returns on digital retrofits and stronger transition incentives (Zheng & Zhang,

2023). Manufacturing digitalization also reshapes the structure and direction of corporate green innovation, driving enterprises to shift from single-technology innovation to full-chain green innovation upgrading (Li et al., 2023).

4.3 Dynamic Evolution Mechanisms of Digital Technology Diffusion

Digital transformation of the energy industry constitutes a dynamic evolutionary process featuring gradual technology diffusion and multi-agent interactive game behavior, rather than static linear upgrading. Ning et al. (2025) deployed complex network evolutionary game models to analyze diffusion laws of digital technologies within the energy industry, finding diffusion speed is jointly shaped by technology costs, policy subsidies, network externalities, and corporate learning capacity. Technology adoption behaviors of core enterprises exert prominent demonstration and spillover effects on entire industrial clusters.

From the perspective of diffusion driving forces, three core drivers exist: technological progress push, market competition pull, and policy regulation guidance. Khan et al. (2022)'s empirical analysis confirmed technological innovation as the core driver of renewable energy development, while iterative cost declines of digital technologies further accelerate penetration within energy sectors. Simultaneously, external pressures including carbon emission reduction policies and environmental regulation force enterprises to pursue digital transformation for efficiency gains and emission cuts, emerging as critical driving forces for technology diffusion (Lu et al., 2020; Rabbi et al., 2022).

5. Practical Pathways for Intelligent Digital and Green Transition of the

Energy Industry

Based on above mechanism and measurement research, scholars have explored multi-level practical pathways for advancing coordinated digital and green development of the energy industry from policy, enterprise, and regional industrial cluster perspectives, forming a multi-layered pathway system.

5.1 Policy Coordination-Driven Pathway: Constructing a Coordinated System of Digital and Green Policies

Policy guidance represents a vital external force advancing energy transition, and coordinated deployment of digital and green policies generates superadditive policy effects exceeding individual policy impacts. Liu & Yao (2026)'s research from the perspective of new quality productive forces found synergistic combinations of intelligent digital and green policies exert far stronger driving effects on corporate green transition than isolated policies, operating via three channels: cutting corporate transition costs, lifting innovation returns, and strengthening market expectations.

Specifically, policy coordination covers three dimensions: first, top-level design coordination, integrating energy digitalization into overall energy transition planning to clarify positioning of digitalization within Dual Carbon targets and avoid fragmented policy frameworks; second, supportive policy coordination, integrating subsidies for digital economy, energy conservation and emission reduction, and R&D to tilt funding toward intelligent digital green transition projects and mitigate corporate capital pressure; third, regulatory policy coordination, establishing accounting standards and certification systems for digital energy conservation and decarbonization, improving connection mechanisms between power markets, carbon markets, and digital platforms to deliver

institutional guarantees for technology deployment (Lu et al., 2020).

Design of sustainable energy policy systems must balance technological progress, business model innovation, and market mechanism improvement to form multi-dimensional coordinated policy frameworks (Lu et al., 2020). Furthermore, energy transition constitutes a long-term systematic project, requiring policy design to balance short-term growth stability and long-term transition promotion, alongside dynamically adjustable policy mechanisms optimized continuously in response to technological advances and industrial development. European transition practices demonstrate that achieving climate targets demands extremely rapid technological transformation speeds, requiring forward-looking and flexible policy frameworks (Victoria et al., 2022; Kober et al., 2020).

5.2 Enterprise Transformation Implementation Pathway: Promoting Integrated Digital and Green Upgrading via Stratified Classification

Enterprises serve as micro entities of energy transition, and differentiated transition pathways must be adopted for entities of varying scales and industries to avoid one-size-fits-all models. Large leading enterprises should leverage technological and capital advantages to conduct deep full-chain intelligent digital retrofits, construct digital twin factories and smart energy management systems, and establish industry transformation benchmarks. Simultaneously, leading enterprises should exert driving effects on industrial chains, exporting digital capabilities to upstream and downstream MSMEs via industrial internet platforms to advance overall industrial chain transformation (Li et al., 2023).

MSMEs should adhere to

lightweight, low-cost, quick-return principles, prioritizing deployment of low-investment, high-return scenarios including energy consumption monitoring and equipment operation and maintenance to gradually elevate digitalization levels. Meanwhile, MSMEs can access digital services via third-party platforms and public service institutions through subscription and shared models to lower one-time investment and technical thresholds (Teng et al., 2022; Zheng & Zhang, 2023). Teng et al. (2022)'s research on MSMEs verified that digital transformation significantly lifts corporate performance, yet enterprises must select adaptation pathways aligned with resource endowments to avoid blind investment.

From core implementation starting points, green technological innovation represents the integration point of corporate digital and green transformation. Enterprises should leverage digital capabilities to elevate R&D efficiency of green technologies, embedding digital technologies across full workflows of product design, manufacturing, operation, and maintenance, realizing energy efficiency improvements and product upgrading via digital innovation (Feng et al., 2022; Yin et al., 2022). Adopting a pressure-state-response framework, Yin et al. (2022) proposed systematic implementation pathways for digital green innovation, noting enterprises must coordinate digital and green targets at the strategic level to construct integrated innovation management systems. Coordination between corporate social responsibility and digital transformation further advances green technological innovation, realizing unification of multiple value dimensions (Zheng & Zhang, 2023).

5.3 Regional Industrial Cluster Coordination Pathway: Building

Ecosystems for Agglomeration and Coordinated Upgrading

Industrial clusters constitute vital organizational forms for regional energy industry development. Factor sharing, technological spillover, and coordinated innovation within clusters effectively reduce individual enterprise transformation costs and elevate overall transition efficiency (Liu & He, 2024). Liu & He (2024)'s research verified coordinated industrial agglomeration drives formation of new quality productive forces and high-quality manufacturing development via scale effects, technological spillover effects, and competition effects, with intelligent digital technologies further strengthening factor mobility and coordination efficiency within clusters.

For new energy industrial clusters, coordinated transition pathways focus on three directions: first, improving cluster digital infrastructure by constructing industry-level industrial internet platforms and big data centers to deliver inclusive digital services for intra-cluster enterprises; second, advancing coordinated transformation of upstream and downstream industrial chains, with leading enterprises drafting unified digital standards to drive synchronous upgrading of supporting MSMEs and lift overall industrial chain coordination efficiency; third, constructing cluster innovation ecosystems integrating R&D resources of universities, research institutes, and enterprises to jointly tackle generic industrial technologies and overcome core technical bottlenecks (Liu et al., 2025; Dong et al., 2023). Research on

digital green innovation interaction mechanisms and dynamic evolution of green building supply chains delivers theoretical references for coordinated green transformation of industrial chains (Dong et al., 2023).

Additionally, cross-regional industrial coordination represents an important direction. Urban agglomerations and metropolitan areas should break administrative barriers to coordinate regional new energy resources, digital resources, and industrial resources, forming differentiated division and coordinated development patterns that avoid homogeneous competition and redundant construction, lifting overall competitiveness of regional industries. Regional innovation capacity acts as a critical mediator between manufacturing intelligent transformation and regional economic development, with coordinated innovation amplifying economic effects of intelligent upgrading (Liu et al., 2025).

5.4 Schematic Logical Text for Practical Pathways of Intelligent Digital and Green Energy Transition

The practical transformation paths of digital-green integration in the energy industry form a multi-level closed-loop operation system covering macro policy, meso industrial clusters and micro enterprises. To clearly sort out the hierarchical division, internal interaction and up-down feedback logic of this multi-dimensional path framework, a systematic closed-loop logical diagram of implementation pathways is drawn and presented in Figure 2.

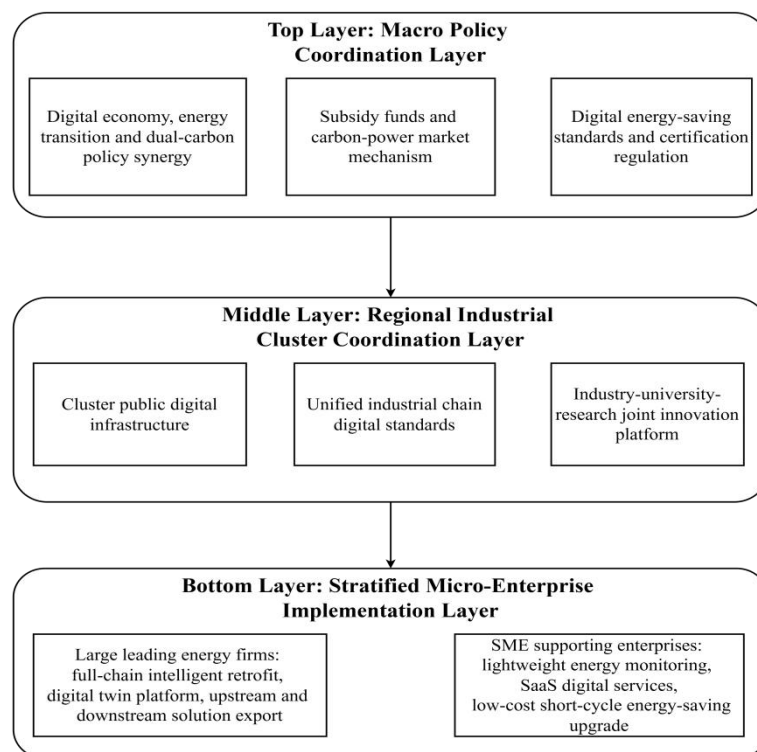


Figure 2. Closed-Loop Logical Framework of Multi-Level Implementation Pathways for Intelligent Digital and Green Transition of Energy Industry

6. Literature Review and Discussion

6.1 Core Consensus Formed by Extant Research

Systematic sorting of global literature published over the past decade confirms unified theoretical consensus within academia regarding intelligent digital technologies and green energy transition, with corresponding conclusions cross-verified via panel empirical analysis, case simulation, and evolutionary game methodologies. First, intelligent digital technologies constitute irreplaceable core support for low-carbon transition of the energy industry. Inderwildi et al. (2020) noted intelligent cyber-physical systems enable closed-loop full-process energy control to realize systematic decarbonization at the source, while domestic scholars Liu et al. (2023) validated via provincial panel data that digitalization significantly cuts carbon emissions through three channels: lifting renewable energy accommodation, optimizing system scheduling, and

reducing end-user energy consumption, with robust decarbonization and efficiency gains from digital empowerment. Second, digitalization and greenization represent bidirectionally coupled symbiotic systems rather than unidirectional driving relationships. Zhang et al. (2025) constructed coupling coordination models and found carbon constraints and energy efficiency demands generated by green transition in turn drive sustained corporate digital investment, while elevated digitalization levels further unlock emission reduction potential, forming mutually reinforcing positive cycles. Third, coordinated integrated development exhibits prominent multi-layered heterogeneity. Pang et al. (2025) and Liu et al. (2025) verified from regional and firm dimensions that economically developed regions and large high-energy-consuming enterprises demonstrate significantly higher coupling coordination degrees, while

MSMEs universally face digital transformation thresholds, rendering one-size-fits-all transition models impractical. Fourth, intelligent digital and green energy transition constitutes a multi-stakeholder collaborative project. Liu & Yao (2026) and Li et al. (2023) both argued autonomous corporate transformation cannot realize overall industrial upgrading, necessitating construction of a collaborative system featuring “government policy guidance – industrial cluster carriers – enterprise implementation – research institute technical support”, with limited effectiveness of isolated policies or individual entities.

6.2 Theoretical Deficiencies in Extant Research

Theoretical frameworks of existing literature exhibit prominent bias toward unidirectional causal logic of “intelligent digital technologies → green energy transition”, with insufficient in-depth interpretation of internal bidirectional coupling mechanisms. On one hand, prevailing coupling research remains confined to indicator measurement, outputting coordination grades via entropy weight coupling coordination degree models without theoretical decomposition of coupling evolutionary stages, critical thresholds, and dynamic transmission chains. Ning et al. (2025) deployed evolutionary game models to confirm critical cost thresholds for digital technology diffusion yet failed to extend analysis to threshold laws governing bidirectional interaction between digitalization and greenization. Extant findings cannot explain why elevated digital input in certain resource-based regions fails to deliver synchronous green transition progress, lacking theoretical interpretation of coupling imbalance and coordination lags. On the other hand, existing theories separate internal linkages between data production factors, technical clusters,

and market mechanisms, predominantly discussing independent application value of individual technologies such as AI and digital twins without constructing integrated “factor – technology – industry” coupling theoretical frameworks centered on data as new production factors. Although Qu et al. (2025) identified synergistic multi-technology effects, they failed to systematically elaborate transmission pathways through which green demand drives iterative digital technology upgrades, leaving theoretical closed loops incomplete.

6.3 Adaptability Deficiencies of Empirical Measurement Systems

Current mainstream coupling measurement indicator systems suffer from generalized and macro-oriented design, with poor adaptability for differentiated regional and micro entity scenarios. Spatially, existing indicators are predominantly constructed based on national and provincial macro statistical data, prioritizing aggregate macro indicators including digital infrastructure investment and regional renewable energy installed capacity, lacking segmented indicators targeting county-level resource-based cities, new energy industrial parks, and private MSME clusters. Pang et al. (2025)’s research on prefecture-level cities in Sichuan found provincial generalized measurement systems underestimate coupling deviations arising from delayed digitalization of county-level MSMEs, failing to capture genuine transition pain points at the county scale. At the micro entity level, most extant research samples consist of listed large energy enterprises, with long-term neglect of MSME energy supporting entities. Liu et al. (2025) verified threshold effects of digital transformation yet failed to design lightweight, low-cost measurement dimensions for MSMEs, hindering quantification of genuine

emission reduction gains from small enterprise digital retrofits. Simultaneously, existing measurement frameworks rarely incorporate negative constraint indicators including data security, digital divide, and technological lock-in, unable to fully reflect comprehensive coupling development levels and generating systematic bias in evaluation outcomes.

6.4 Insufficient Practicality of Transition Path Research and Gaps in Risk Mechanism Research

Prevailing pathway research prioritizes top-level macro policy design, with insufficient supply of actionable solutions for segmented industries and micro entities. Policy research predominantly focuses on macro tools including subsidies and planning, lacking differentiated policy combinations segmented for distributed photovoltaics, virtual power plants, integrated energy services, and other sub-sectors. Enterprise research merely distinguishes large and small enterprises without designing exclusive transition pathways segmented for thermal power, wind-solar new energy, energy storage, and integrated energy service industries. While Teng et al. (2022) proposed lightweight transition frameworks for MSMEs, they failed to deliver replicable business models, cost-sharing mechanisms, and third-party service pricing frameworks for practical deployment. Meanwhile, extant research universally neglects multiple latent risks emerging during transition: first, digital divide risks, wherein widening digital gaps between developed and underdeveloped resource regions exacerbate regional transition imbalance; second, technological lock-in risks, wherein large-scale corporate investment in single digital architectures generates sunk costs due to incompatibility with subsequent green technology iterations; third, data security

and privacy risks, including leakage and tampering hazards from open distributed energy transaction and end-user load data. Ahl et al. (2022) only mentioned multi-dimensional constraints on blockchain deployment without constructing full-industry-chain frameworks for risk identification, early warning, and prevention, leaving prominent research gaps in risk dimensions.

6.5 Limitations of Research Methods and Perspectives

Methodologically, most extant empirical analysis deploys static panel regression and cross-sectional coupling models, lacking dynamic spatial econometrics and long-term evolutionary simulation analysis to capture dynamic spatiotemporal evolution characteristics of coupling relationships between digitalization and greenization. Evolutionary game models predominantly focus on single corporate decision-making without incorporating multi-stakeholder interactive games among governments, power grid operators, park developers, and carbon trading platforms. From a research perspective, most literature adopts supply-side viewpoints centered on energy production and transmission digital retrofits, with insufficient excavation of bidirectional coupling mechanisms on the demand side including end-user demand response, residential energy digitalization, and market-oriented trading within energy communities. Cross-sector integration perspectives remain fragmented, with coupling mechanisms for coordinated digital decarbonization across energy, transportation, construction, and agriculture limited to case enumeration without unified analytical frameworks.

7. Conclusions and Future Outlook

This paper systematically reviews global research outcomes regarding

intelligent digital technologies empowering green energy transition, constructing a complete analytical framework spanning “technical systems – functional mechanisms – coupling measurement – practical pathways” to clarify core research threads within the field. The study verifies that artificial intelligence, digital twins, industrial IoT, and blockchain form integrated intelligent digital technical foundations covering full energy industrial chains and extending to cross-sectoral scenarios of transportation, construction, and agriculture. Intelligent digital technologies drive industrial decarbonization via three mechanisms: optimizing production factor allocation, lifting full-chain energy efficiency, and reconstructing industrial value chains. Digitalization and greenization feature bidirectional coupling characteristics, with coupling coordination levels exhibiting multi-layered heterogeneity across regions, industries, and enterprises. Advancement of transition requires coordinated efforts spanning macro policy, meso industrial cluster, and stratified micro enterprise layers. Comparative analysis of global literature confirms extant research has completed foundational application verification, macro mechanism testing, and generalized measurement system construction, forming unified core theoretical consensus. Nevertheless, prominent research gaps persist across four dimensions: dynamic bidirectional coupling mechanisms, differentiated empirical research segmented for regional and micro enterprise scales, deployable transition pathways, and transition risk prevention and control. Existing theoretical and empirical conclusions cannot fully align with practical demands of differentiated energy industrial transition across China.

Faced with practical demands of advancing Dual Carbon targets,

constructing new power systems, and developing new quality productive forces, subsequent research can deepen and expand along four core directions. First, improve dynamic theoretical frameworks for bidirectional coupling, adopting synergy theory and complex system theory to break traditional unidirectional empowerment perspectives, constructing complete closed-loop transmission frameworks of “intelligent digital technologies empowering green transition – green emission reduction demands driving iterative digital technology upgrades”, identifying staged evolutionary characteristics, critical thresholds, and imbalance inducements of coupling systems to compensate deficiencies of static extant theories. Second, advance differentiated empirical research segmented for micro scales, sinking analytical scope to county-level regions, industrial parks, and MSME industrial clusters, abandoning generalized macro indicators and constructing exclusive coupling measurement systems adapted to resource-based cities, private industrial clusters, and distributed new energy bases to quantify transition constraints and emission reduction potential under diverse scenarios. Third, focus on innovative deployable models for micro entities, excavating transition pain points of enterprises with varying scales, ownership types, and segmented industrial sectors via field research and questionnaire interviews, designing lightweight, low-cost, replicable integrated digital and green business models for MSMEs, and improving supporting mechanisms for cost sharing, risk allocation, and inclusive third-party services to lift practical value of research outcomes. Fourth, construct multi-policy coordination and transition risk prevention and control systems, identifying optimal combined policy instruments for digital, energy,

environmental, and industrial policies via econometric simulation, establishing dynamically adjustable policy adaptation mechanisms. Systematically identify transition risks including digital divide, technological lock-in, data security, and computing power energy consumption, constructing integrated frameworks for risk identification, early warning, and governance to fill risk dimension gaps in extant research, delivering more complete and practically aligned theoretical support for coordinated high-quality digital and green development of China's energy industry nationwide.

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