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Green Finance and the Decarbonization of Digital Resources: A Comparative Analysis of Embedding Mechanisms and Functional Evolution

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Abstract

This paper aims to dissect the deep-seated mechanisms of green finance in the critical area of digital resource development. Facing the immense energy consumption brought by the high-speed development of the digital economy and the urgent constraints of "dual carbon" goals, green finance has surpassed its traditional role as a financing tool. By integrating institutional embeddedness and evolutionary economics theories, this paper constructs a multi-level embedded analysis framework of "macro-institution–meso-industry–micro-technology" and proposes a three-stage model for the functional evolution of green finance: "compliance-driven financing," "strategic integration," and "ecological co-evolution." The study finds that green finance is deeply embedded in the entire lifecycle of digital resources (especially data centers) through mechanisms such as policy guidance, market standards, industrial chain penetration, and technological integration. Its function evolves from passive financing to meet external compliance requirements to an endogenous strategy for enhancing core corporate competitiveness, and is ultimately expected to foster a data-driven green innovation ecosystem against the backdrop of the marketization of data elements. The research in this paper provides a new theoretical perspective for understanding the dynamic role of green finance in the digital age and offers beneficial insights for relevant policy-making and market practices.

Keywords Green Finance; Digital Resources; Embedding Mechanism; Functional Evolution; Data Center; Data Elements

1 Introduction: The Symbiosis and Conflict of Global Digital Expansion and Carbon Neutrality

1.1 The Core Tension: The Infinite Growth of the Digital Economy and the Finite Boundaries of the Planet

The rapid development of the digital economy is pushing global society into a profound structural contradiction. On one hand, digital technology is seen as a key enabling force for achieving sustainable transformation, providing unprecedented solutions to climate change by optimizing resource allocation,

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improving energy efficiency, and promoting industrial collaboration. However, on the other hand, its physical foundation—digital infrastructure centered on data centers—is rapidly becoming a "new highland" of global energy consumption, posing a severe challenge to global carbon neutrality goals.

This contradiction has been dramatically amplified by the Artificial Intelligence (AI) revolution. According to the International Energy Agency (IEA), global data center electricity consumption reached 460 terawatt-hours (TWh) in 2022 and is projected to potentially double to a staggering 1,000 TWh by 2026. This figure would account for approximately 5% of total global electricity consumption, equivalent to the current total electricity consumption of Japan[2]. The training and inference processes of AI require immense and uninterrupted computing power, which not only leads to a surge in electricity demand but also places enormous pressure on grid stability and water supply systems[5]. McKinsey & Company predicts that by 2030, merely meeting the computing power demand related to AI will require up to $5.2 trillion in capital for data center construction. This conflict between the infinite growth potential of the digital economy and its finite environmental carrying capacity constitutes the starting point of this paper's research and provides the fundamental impetus and broad arena for the deep intervention of green finance.

This inherent tension reveals the core paradox of digitalization: while digital technology helps other industries to "decarbonize," its own "carbon footprint" is expanding at an unprecedented rate. It is both a "solution" to the climate problem and a "source" of the problem. How to resolve this dilemma and achieve the sustainable development of the digital economy has become a core global issue.

1.2 Research Positioning in the International Academic Dialogue: Opening the "Mechanism Black Box"

In the international academic community, the discussion on the relationship between green finance and the digital economy has achieved fruitful results. Recent studies published in authoritative journals such as the *Journal of Cleaner Production* and *Energy Policy*, through empirical analysis of G20 countries and other regions, have generally confirmed a significant positive synergistic effect between green finance and digital economy development at the macro level. Together, they promote the growth of renewable energy and the reduction of carbon emission intensity. Some studies further point out that green technology innovation is a key intermediary variable connecting the two, meaning that green finance provides the necessary financial support for green technology research and development driven by the digital economy.

However, while existing research has revealed a positive "correlation" at the macro level, it has also exposed a clear "mechanism black box". Most studies have failed to delve into the institutional and organizational "mechanisms" behind it. How exactly does green finance transform from an external, project-oriented financing tool into a structural force that is deeply integrated within the digital industry, reshaping its technological pathways and business models? What differentiated paths does this process exhibit under different political and economic systems (for example, China's state-led model, the European Union's regulation-driven model, and the United States' market-incentive model)? Systematic, cross-national comparative studies based on empirical evidence are still lacking.

This paper aims to fill this research gap. The objective of this study is not simply to re-verify the positive correlation between the two, but to open this "mechanism black box," deeply analyze the multi-level embedding mechanism of green finance in the development process of digital resources, and, through cross-national comparison, reveal how different institutional environments have shaped the diversified paths of this industry-finance integration process.

1.3 Theoretical Contributions and Research Structure

The core theoretical contribution of this paper is to validate, revise, and deepen the "embedding-evolution" integrated analytical framework proposed by the author in previous research, through empirical data and cross-national comparison. The revision goal of this paper is clear: not only to explain "what" the structural linkage relationship between green finance and digital resource development is, but also to explain "how" this relationship evolves in different institutional environments through comparative analysis and quantitative evidence.

To achieve this goal, the structure of this paper is as follows: The second part will formally introduce the "embedding-evolution" integrated analysis framework and provide a structured review of the role of financial technology (FinTech) as a systemic enabling tool. The third part is the core empirical chapter of this paper, which will conduct an empirical test of the "embedding" mechanism through a comparative analysis of three typical models—China, the European Union, and the United States—as well as a quantitative analysis of data from leading global data center operators, extending the cases to emerging computing power fields such as Artificial Intelligence (AI) and blockchain. The fourth part will, based on the aforementioned empirical analysis, re-validate the three-stage model of the functional evolution of green finance and look ahead to the future prospects of the third stage, "ecological co-evolution." The fifth part provides conclusions and policy implications. Through this structure, this paper aims to provide a more universal and explanatory theoretical framework for understanding the green industry-finance integration in the digital age.

2 A Dynamic Framework for Analyzing Green-Digital Co-evolution

2.1 The "Embedding-Evolution" Integrated Analysis Framework

To systematically analyze the complex role of green finance in the development of digital resources, this paper constructs a dynamic analytical framework that integrates Institutional Embeddedness and Evolutionary Economics. This framework includes two complementary analytical dimensions, aiming to simultaneously explain the structural characteristics and dynamic evolution process of the industry-finance integration.

Institutional Embeddedness (Static Lens): Drawing on Granovetter's classic theory, this paper argues that economic actions are not isolated but are deeply rooted in the institutional environment, social networks, and cultural cognition in which they are situated. This paper extends this theory to the intersection of green finance and digital resources, analyzing from three levels how green finance achieves structural "coupling" with digital resource development through multiple pathways at a specific point in time, thereby answering the "what" question.

Macro-institutional Embeddedness: This refers to the shaping of green finance activities by a combination of national top-level strategies, industrial policies, financial regulatory laws, and internationally recognized standards. These macro-institutions constitute the fundamental rules and sources of legitimacy for green finance's intervention in digital resource development.

Meso-industrial Embeddedness: This indicates that green finance capital is not simply injected into enterprises but systematically penetrates along the industrial chain and the entire lifecycle of digital resources (especially data centers). By linking financing conditions to industry-specific performance indicators (such as Power Usage Effectiveness, PUE), financial logic is embedded in corporate investment, construction, procurement, and operational decisions[1].

Micro-technological Embeddedness: This refers to the deep integration of financial services with the internal logic of digital technology, giving rise to new product forms, service models, and application scenarios. In this embedding, finance is no longer an external supporter of technology but becomes an integral part of the solution along with technology.

Evolutionary Economics (Dynamic Lens): Drawing on the evolutionary theory of Nelson and Winter, this paper views the interaction between the two as a process of Co-evolution, focusing on the dynamic changes, path dependence, and selection-variation-inheritance mechanisms of the economic system. This dimension aims to answer the "how" question. In this process, global climate change and the "dual carbon" goals constitute a powerful external "selection pressure." In response to this pressure, financial institutions and digital enterprises continuously generate "variations"—that is, innovative financial tools, business models, and green technologies. Those "variations" that can better balance economic and environmental benefits are selected and amplified by the market. Successful practices spread through learning and imitation effects and gradually solidify into industry standards and conventions, forming a new "path dependence," thereby promoting the functional evolution of green finance from simple to complex and from exogenous to endogenous.

2.2 FinTech as a Systemic Enabling Tool: A Structured Review

In response to the reviewer's comments, this section provides a structured analysis of the role of FinTech based on the latest systematic review research. FinTech is not a simple collection of isolated technologies but rather a systemic enabling layer that fundamentally reshapes the operational logic of green finance[8]. Its core functions can be summarized into the following three points:

Enhancing Transparency and Credibility to Combat "Greenwashing": Centered on blockchain technology, FinTech can achieve full-process tracking of green funds from fundraising and investment to benefit assessment by building a decentralized, immutable distributed ledger. For example, in the green bond market, smart contracts based on blockchain can automatically execute the allocation of funds and environmental benefit reporting clauses, ensuring that funds are used for their intended purpose. This technically curbs the "greenwashing" behavior of diverting funds to non-green projects, significantly enhancing market credibility[8].

Optimizing Risk Assessment and Pricing for Precision Irrigation: Centered on Artificial Intelligence (AI) and big data analytics, FinTech can integrate massive, unstructured Environmental, Social, and Governance (ESG) data (such as satellite remote sensing imagery, supply chain carbon footprints, and online public opinion) to build dynamic and precise ESG rating and climate risk analysis models. This enables financial institutions to go beyond the static reports voluntarily disclosed by companies to quantitatively assess the "greenness" of projects and potential environmental risks. These non-financial risks are internalized as core variables in credit approval, insurance pricing, and investment decisions, achieving a shift from "qualitative judgment" to "quantitative risk control"[8].

Reducing Costs and Barriers to Promote Inclusivity and Innovation: Through digital platforms and Decentralized Finance (DeFi) models, FinTech can significantly reduce the transaction costs and participation barriers of green financial services. This not only makes it more convenient for small and medium-sized enterprises to obtain green financing but also gives rise to inclusive financial innovations targeting the consumer end, such as personal carbon accounts (for example, China's "Ant Forest"), extending the incentive mechanism of green finance to the daily behaviors of the public.

Despite its great potential, the application of FinTech in the green finance field still faces severe challenges, including a lack of data standardization, lagging regulatory frameworks, algorithmic bias, and the digital divide. The analysis in this paper will examine these technological mechanisms within specific institutional contexts.

3 The Multi-Level Embedding of Green Finance: An Empirical and Comparative Analysis

This section will conduct an empirical test of the "embedding" framework through a comparison of three models—China, the European Union, and the United States—and a quantitative analysis of data from leading global data center operators.

3.1 Macro-institutional Embedding: A Comparative Analysis of Policy Frameworks in China, the EU, and the US

The top-level rules for green finance's intervention in digital resource development present three distinctly different models globally. These models profoundly influence the direction, speed, and conditions of capital flow and reflect their respective unique political-economic systems and governance logics.

China's National Strategy-Driven Model: China's model is a typical top-down, strong-push type led by national strategy. Its core feature is the high degree of coordination between industrial policy and financial policy. The proposal of the "dual carbon" goals set the highest-level political agenda for the entire economic and social transformation. Under this framework, documents issued by industrial authorities such as the Ministry of Industry and Information Technology, like the *Three-Year Action Plan for the Development of New Data Centers*, explicitly set energy efficiency indicators such as PUE (Power Usage Effectiveness) as hard constraints for data center development. At the same time, financial regulatory authorities such as the People's Bank of China (PBOC) systematically guide financial resources towards green and low-carbon fields by building a green financial system and implementing green finance performance evaluations for financial institutions. In particular, the "Eastern Data, Western Computing" project, through a national-level layout of computing power hubs, directly guides data center construction to the western regions, which are rich in renewable energy. This itself is a grand combination of industrial and energy policy, creating clear scenarios and demands for targeted investment by green finance. The advantage of this model lies in its ability to concentrate resources to achieve major goals, quickly overcoming market failures and coordination obstacles, but it may also face challenges in terms of efficiency and flexibility.

The European Union's Regulation and Standard-Led Model: The EU's model is a typical regulation-driven, rules-setting type centered on standard-building. Its cornerstone is the *EU Taxonomy for Sustainable Activities*, a regulation that provides a unified, detailed legal definition and Technical Screening Criteria for "sustainable economic activities". For data centers (Activity 8.1: "Data processing, hosting and related activities"), the Taxonomy explicitly requires compliance with the best practices of the *EU Code of Conduct on Data Centre Energy Efficiency* and sets out detailed "Do No Significant Harm" (DNSH) provisions regarding PUE, water use, and the circular economy. Additionally, the revised *Energy Efficiency Directive* (EED) mandates that large data centers publicly disclose key performance indicators including PUE, energy consumption, and waste heat recovery. This practice of legally establishing "green" standards and information disclosure obligations provides the market with clear, stable, and mandatory expectations, aiming to guide capital by enhancing transparency and standardization and to fundamentally prevent "greenwashing."

The United States' Fiscal Incentive-Driven Model: The US model relies more on market mechanisms and large-scale fiscal incentives. Its core policy tool is the *Inflation Reduction Act* (IRA) passed in 2022. The IRA does not set specific energy efficiency standards for data centers like the EU but significantly reduces the costs of renewable energy, energy storage systems, and energy efficiency retrofits for commercial buildings by providing substantial investment tax credits (ITC) and production tax credits (PTC). For example, Section 179D provides considerable tax deductions for energy-saving retrofits of commercial buildings, and data centers, as energy-intensive commercial buildings, are direct beneficiaries of this provision. The logic of this model is not to mandatorily define "what is green" but to make investing in green technology and purchasing green energy economically attractive by changing the cost-benefit structure, thereby guiding the private sector to make green choices spontaneously.

The differences among these three models shape the different strategies that companies use to embed green finance in different markets. A globally operating data center company must closely follow national strategic planning in its business development in China, strictly adhere to the compliance requirements of the Taxonomy in Europe, and maximize the tax benefits brought by the IRA in the United States. This heterogeneity of macro-institutions is key to understanding the diversity of corporate behavior at the meso-industrial level and also reveals that there is no one-size-fits-all "optimal" policy model, but rather an institutional evolution under various path dependencies (Table 1).

Table 1: A Comparative Analysis of Green Finance Policies for Digital Infrastructure (China, EU, US)

Feature	China	European Union	United States
Main Policy Driver	National strategic directive	Market regulation and standardization	Fiscal incentives and market competition
Core Policy Tools	"Dual Carbon" goals, "Eastern Data, Western Computing" project, industrial energy efficiency standards	EU Taxonomy for Sustainable Activities, Energy Efficiency Directive (EED)	Inflation Reduction Act (IRA)
Key Regulatory Bodies	People's Bank of China (PBOC), National Development and Reform Commission (NDRC), Ministry of Industry and Information Technology (MIIT)	European Commission, Joint Research Centre (JRC)	Department of the Treasury, Internal Revenue Service (IRS), Environmental Protection Agency (EPA)
Core Mechanism	Mandatory targets (PUE, renewable energy ratio), directed credit guidance	Detailed Technical Screening Criteria (TSC), mandatory information disclosure	Investment/Production Tax Credits (ITC/PTC), tax deductions (179D)
Impact on Financial Markets	Guides large-scale investment from state-owned capital and policy banks	Creates a standardized, transparent green investment market	Significantly reduces the risk and cost of private sector green investment through subsidies

3.2 Meso-industrial Embedding: Quantitative Evidence from Leading Global Data Center Operators

At the meso-industrial level, green finance has reshaped the industry value chain by deeply integrating with corporate core strategies and financial performance. This section provides quantitative evidence for this embedding process by analyzing the latest public data from leading global operators.

Leading global data center operators, such as Equinix, Digital Realty, and China's GDS Holdings and Chindata Group, have widely upgraded green finance from an alternative financing channel to a core corporate capital strategy. They are no longer financing individual "green projects" sporadically but have established company-level *Green Finance Frameworks*. These frameworks systematically articulate the companies' sustainable development goals and follow internationally recognized *Green Bond Principles* (GBP) and *Green Loan Principles* (GLP), deeply linking the companies' ESG commitments with their financing activities, forming a closed-loop management system from strategic commitment, project screening, and fund management to impact reporting.

Behind this strategic shift is a profound corporate understanding of the economic logic of green development. A lower PUE is directly equivalent to lower operating costs (OPEX), which is particularly crucial in the data center industry where electricity costs are dominant. At the same time, excellent ESG performance can attract a broader range of long-term investors (such as pension funds and sovereign wealth funds), thereby reducing the cost of capital and winning the trust of an increasing number of corporate clients with sustainable development requirements. Quantitative data shows that this strategy has translated into tangible financing scale and environmental benefits:

Equinix: As one of the world's largest data center REITs, Equinix had issued and fully allocated $4.9 billion in green bonds by early 2024. These funds were invested in 172 green building projects, 33 energy efficiency improvement projects, and multiple renewable energy Power Purchase Agreements (PPAs). According to its report, these investments can achieve an annual reduction of over 669,000 metric tons of CO2 equivalent (mtCO2e). On the operational level, Equinix achieved 96% renewable energy coverage in 2023, with the global average PUE dropping to 1.39.

Digital Realty: Also a leader in the green bond market, Digital Realty had completed the allocation of $7.2 billion in green bonds by 2024. The projects supported by its green bonds have cumulatively avoided 1.7 million metric tons of CO2 equivalent emissions and generated 1.3 million megawatt-hours (MWh) of renewable energy electricity. The company achieved 75% renewable energy coverage globally in 2024.

GDS Holdings: As a leading third-party operator in China, GDS more commonly adopts Sustainability-Linked Financing. In 2023, the company issued the country's first data center sustainability-linked asset-backed security (ABS), directly linking the financing terms to specific ESG performance indicators such as PUE and renewable energy usage ratio. Operationally, GDS achieved a 40% renewable energy usage rate in 2024 and optimized its average PUE from 1.28 in 2023 to 1.24, which led to an upgrade of its MSCI ESG rating to A.

Table 2: Empirical Indicators of Green Finance Practices by Leading Data Center Operators (Based on 2023-2024 Reports)

Indicator	Equinix	Digital Realty	GDS Holdings
Green Financing Scale (cumulatively allocated)	$4.9 billion+ (Green Bonds)	$7.2 billion+ (Green Bonds)	Scale not disclosed, primarily Sustainability-Linked Loans/ABS
Main Financing Instruments	Green Bonds	Green Bonds	Sustainability-Linked Loans/ABS
Renewable Energy Coverage (%)	96% (2023)	75% (2024)	40% (2024)
Average PUE	1.39 (2023)	Continuous improvement, specific value not centrally disclosed	1.24 (2024)
Annualized Carbon Reduction (mtCO2e)	> 669,000	Annualized data not disclosed, cumulative avoidance of 1.7 million tons	Carbon intensity decreased by 15.8% YoY (2024)
Climate Goals	100% renewable energy coverage by 2030	68% reduction in Scope 1 & 2 emissions by 2030	Carbon neutrality by 2030

Chindata Group: Before its acquisition, Chindata also actively utilized green finance tools. The company had collaborated with banks like DBS to obtain green loans compliant with international standards to support the construction of its green data center campuses. Operationally, the company reported an average PUE of 1.21 in 2022 and committed to achieving 100% renewable energy use by 2030.

These data clearly indicate that the embedding of green finance is no longer an external, complianceoriented decoration but has been internalized into a core strategy for companies to reduce operating costs, optimize capital structure, and enhance market competitiveness. Environmental performance indicators (such as PUE) have been "financialized" and are directly linked to corporate financing costs through instruments like Sustainability-Linked Loans/Bonds (SLLs/SLBs). This integration of financial logic and environmental performance is profoundly reshaping the investment, construction, and operation models of the data center industry (Table 2).

3.3 Micro-technological Embedding: Expanding to Frontier Practices in AI and Blockchain

To enhance the universality of the theoretical framework, this section expands the case analysis from traditional data centers to emerging digital resource fields that pose more extreme challenges to energy consumption: blockchain computing power and AI training platforms. In these frontier areas, the integration of finance and technology has reached an unprecedented depth.

Blockchain and Green Computing Power Financing: Blockchain networks based on Proof-of-Work, represented by Bitcoin, are heavily criticized for their huge energy consumption. However, the industry is evolving towards more energy-efficient consensus mechanisms (such as Proof-of-Stake). The embedding of green finance in this field is reflected in the precise support for "green computing power." For example, financial instruments are used to support blockchain projects that adopt energy-saving consensus mechanisms or to provide specialized financing for data centers that use renewable energy for cryptocurrency "mining". A deeper level of technological embedding is manifested in the use of blockchain technology itself to serve green finance. For instance, by issuing "tokenized" green bonds, bond assets are put on the chain, and smart contracts are used to achieve automated tracking of fund flows and real-time verification of environmental benefits. This not only significantly reduces issuance and regulatory costs but also enhances market transparency and liquidity.

Artificial Intelligence and Energy Procurement Innovation: The training and inference of AI models require massive, uninterrupted computing power, posing unprecedented demands on the scale and stability of the power supply. This creates a huge new market for green finance. Against this backdrop, an important financial innovation—the corporate Power Purchase Agreement (PPA)—is becoming a key tool for tech giants to secure long-term, stable, and renewable electricity for their AI clusters. A PPA is a financial contract in which a tech company commits to purchasing electricity from a specific renewable energy project (such as a new wind farm or solar power station) at a fixed price over a period of 10-20 years. This long-term commitment provides renewable energy project developers with stable revenue expectations, enabling them to obtain the necessary project financing for construction. This is a typical deep integration of industry and finance: financial capital (supporting the PPA) enables the production of green electricity, which in turn becomes a prerequisite for the sustainable development of AI computing power. Furthermore, AI technology itself is being used in reverse to optimize PPA strategies. By analyzing multi-dimensional variables such as energy market prices, meteorological data, and grid load through predictive analysis, AI helps companies choose the optimal timing and pricing structure for contracts, thereby optimizing risk and return.

From the greening of blockchain to the sustainable assurance of AI computing power, the logic of micro-technological embedding becomes increasingly clear: finance is no longer just an external supporter of technology but is deeply integrated with the choice of technological paths, energy procurement models, and even the construction of business models, becoming an indispensable core component of the solution.

4 Re-validating the Functional Evolution of Green Finance

This section will, in conjunction with the preceding empirical and comparative analysis, provide a more solid basis of argumentation for the three-stage evolution model of "compliance-driven financing," "strategic integration," and "ecological co-evolution."

4.1 Basis for Delineating Evolutionary Stages

The reviewer requested a clearer basis for the stage delineation. This paper argues that the evolution of stages is not determined by a single point in time but is jointly driven by key turning points in policy signals, market cognition, and technological paradigms.

Stage One (Nascent Stage): Compliance-driven Financing. The starting point of this stage can be traced back to around 2015, marked by the signing of the Paris Agreement and the initial formation of the international Green Bond Principles. During this period, green finance was primarily a tool to meet external compliance or corporate social responsibility (CSR) image needs. Its typical feature was project-oriented financing, for example, issuing a special-purpose green bond for a single data center that had obtained a green building certification like LEED. The financing behavior had a weak connection to the overall corporate strategy, and the assessment by financial institutions was mainly focused on a "checklist" review of whether the project met the standards of a green catalogue.

Stage Two (Growth Stage): Strategy-driven Integration. The turning point for this stage appeared between 2020 and 2024, marked by significant events including China's proposal of the "dual carbon" goals (2020), the official entry into force of the EU's Sustainable Finance Taxonomy (2020), and the enactment of the US Inflation Reduction Act (2022). These major macro-institutional changes, combined with the market trend of ESG investment becoming mainstream, jointly prompted a qualitative shift in corporate cognition. Companies began to realize that excellent ESG performance could be directly translated into financial advantages—lower operating costs and capital costs. The typical feature of this stage is entity-oriented financing. Companies began to establish company-level Green Finance Frameworks and adopted Sustainability-Linked Loans/Bonds (SLLs/SLBs) linked to the overall ESG performance of the company, internalizing sustainable development as a component of corporate governance and core competitiveness. The quantitative data of the leading operators in the third part is strong evidence of this stage.

Table 3: Stage-wise Characteristics of the Functional Evolution of Green Finance

Evolution Stage	Functional Positioning	Core Driver	Main Financial Instruments	Target Object	Embedding Depth	Typical Manifestation
Stage One: Nascent	Compliance-driven Financing	External policy pressure, corporate image	Special-purpose green loans, project-level green bonds	Single green projects (e.g., green buildings)	Surface Embedding: Project compliance level	Single financing for a data center that has obtained LEED certification.
Stage Two: Growth	Strategic Integration	Endogenous economic benefits, market competitive advantage	Company-level green finance frameworks, Sustainability-Linked Loans/Bonds (SLL/SLB)	Corporate entity (overall ESG performance)	Mid-level Embedding: Corporate strategy and governance level	Linking financing costs to the company's overall PUE, renewable energy usage ratio, and other KPIs.
Stage Three: Co-evolution	Ecosystem Building	Marketization of data elements, value co-creation	Green data asset securitization, data-driven green innovation funds, carbon-inclusive platforms	Data elements (intangible assets) and digital ecosystem	Deep Embedding: Core assets and business model level	Providing value certification and financial incentives for "green data," building a data-driven green innovation ecosystem.

Stage Three (Co-evolution Stage): Ecosystem-building Co-evolution. This is a forward-looking perspective on the current and future direction of evolution, driven by two emerging paradigms: first, the explosive growth in computing power demand brought about by the AI technology boom, and second, the advancement of the "market-oriented allocation of data elements" reform. In this stage, the object of green finance's role will expand from tangible physical infrastructure (data centers) to intangible core digital assets (the data itself), and its function will also evolve from supporting individual enterprises to building an entire green digital ecosystem.

This evolutionary path is not a simple linear progression but a co-evolutionary process of "selection-variation-inheritance" jointly shaped by policy, technology, and the market. The external environment (such as climate change) imposes strong "selection pressure," prompting enterprises and financial institutions to generate "variations" (innovative financial tools and business models). Successful variations (such as SLLs) are selected and amplified by the market and spread through learning and imitation, eventually solidifying into industry practices and forming a new "path dependence," thereby driving the system to evolve to a more advanced stage (Table 3).

4.2 Focusing on the Third Stage: An Ecological Outlook for Green Data and Sustainable Computing Power

The original text's discussion of the third stage was relatively forward-looking; this section will deepen it in light of the latest trends. As data is formally established as a factor of production alongside labor, capital, and technology, its "attributes" will become critically important. This opens up a completely new space for green finance to play a role—moving from "greening hardware" to "greening data."

Embedding in Data Property Rights and Transactions: The entire process of data generation, processing, storage, and transmission is accompanied by a carbon footprint. In the future, the environmental attributes of data—for example, whether it is processed by "green computing power" driven by 100% renewable energy—may become a key dimension in its value assessment and market pricing. Green finance can innovate a series of services for this: providing credit enhancement services for certified "green data assets," thereby increasing their value in the data trading market; developing securitized products with green data sets as the underlying assets; or supporting the construction of blockchain-based "data carbon footprint" tracking and certification platforms, deeply embedding green principles into the value discovery and market circulation processes of data elements.

Supporting Data-Driven Green Innovation: The marketization of data elements will greatly enhance the availability and transparency of environmental data, which in turn provides a high-quality data foundation for precise decision-making in green finance. Green finance can establish special funds to invest in innovative enterprises that use massive environmental data for climate model prediction, circular economy model design, and the development of new green technologies. This will form a virtuous cycle of "marketization of data elements → improved quality of environmental information → precise support from green finance → catalysis of green technology innovation → generation of higher-value green data," constituting a data-driven green innovation ecosystem.

Building New Benefit-Sharing Mechanisms: In the spirit of policies like the "Data Twenty Articles," the distribution of benefits from data elements should reflect both efficiency and fairness. Green finance can participate in designing innovative benefit-sharing mechanisms that reflect the environmental contributions of data. For example, by establishing green data public welfare funds, part of the proceeds from data transactions can be invested in environmental protection projects; or through the design of financial instruments, individuals or enterprises that provide society with data having high environmental positive externalities (such as low-carbon behavior data contributed by individuals through carbon-inclusive platforms) can receive additional economic returns, thereby unifying data value, economic value, and environmental value.

5 Conclusion and Policy Implications

5.1 Summary of Research Conclusions

By integrating the theories of institutional embeddedness and evolutionary economics, and combining a comparative analysis of the three major economies of China, the US, and the EU with a quantitative examination of leading global enterprises, this paper systematically studies the mechanisms of action and dynamic evolution of green finance in the development of digital resources. The main conclusions are as follows:

Regarding the embedding mechanism: Green finance does not simply provide funds for digital resource development but is deeply embedded in its development process through a multi-level mechanism system of "macro-institution–meso-industry–micro-technology." At the macro level, the policy frameworks of different countries (China's state-strategy-driven, the EU's regulation-and-standard-led, and the US's fiscal-incentive-driven) shape distinctly different top-level rules and incentive structures. At the meso level, capital penetrates along the entire lifecycle of digital resources such as data centers, reshaping the industrial value chain by linking ESG performance with core corporate financial performance. At the micro level, the logic of finance is deeply integrated with digital technologies (such as AI and blockchain), giving rise to new scenarios like precise environmental risk pricing, sustainable computing power assurance, and inclusive green applications.

Regarding functional evolution: The evolutionary path of green finance's function is supported by empirical evidence, which shows that it has gone through a three-stage evolution from "compliance-driven financing" to "strategic integration," and is now moving towards "ecological co-evolution." The essence of this process is the transformation of green finance's role from an exogenous variable meeting external compliance requirements to an endogenous variable enhancing core corporate competitiveness; its object of action has also deepened from tangible physical infrastructure (data centers) to intangible core digital assets (data elements). This evolutionary path profoundly reflects the historical trend of the digital economy and the green economy moving from preliminary combination to deep integration, and ultimately towards co-evolution.

5.2 Theoretical Contributions

The theoretical contribution of this paper lies in providing a dynamic, multi-dimensional analytical framework that has been empirically tested and strengthened through international comparison for studying the issue of green finance in the digital economy era. By applying the "embedding-evolution" framework to a cross-national comparison, this paper transcends the traditional unidirectional enabling or linear causal analysis, revealing how the macro-institutional environment influences micro-technical practices through meso-level organizational strategies. This provides a new theoretical perspective and analytical tool for understanding the complexity and diversity of industry-finance integration in the context of globalization.

5.3 Policy Implications

Based on the above research, to better leverage the role of green finance in promoting the sustainable development of digital resources, this paper proposes the following targeted policy implications:

For regulatory agencies: Strengthen policy coordination and international standards dialogue: Further promote deep coordination between digital industry policies (such as computing power planning, energy consumption indicators) and green finance policies (such as green catalogues, information disclosure requirements). At the same time, actively participate in the international coordination of green finance standards (such as taxonomies) to promote the convergence and mutual recognition of standards, thereby reducing the compliance costs for multinational enterprises and investors and promoting the effective flow of global green capital.

Develop innovative regulatory technology (RegTech): Use digital technologies such as big data and blockchain to build an intelligent green finance regulatory platform. This platform should be able to achieve real-time, transparent monitoring of green fund flows and the environmental benefits of projects, effectively identify and prevent "greenwashing" risks, and improve regulatory efficiency and precision.

Proactively lay out the green governance of the data element market: In the process of promoting the reform of market-based allocation of data elements, proactively research and design a top-level institutional framework that embeds Environmental, Social, and Governance (ESG) principles into the definition of data property rights, circulation and trading, and benefit distribution. Encourage pilot projects for the certification, valuation, and trading of "green data," guiding the data element market to have a "green gene" from its inception.

For financial institutions: Deepen product and service innovation: Go beyond traditional green credit and bonds to develop innovative green financial products that are better matched with the technological characteristics and business models of the digital industry (such as the high energy consumption of AI computing power and the distributed nature of blockchain). For example, design financial instruments linked to more refined indicators such as computing power energy efficiency (e.g., EFLOPS/W), data carbon footprint, and waste heat utilization rate, to provide comprehensive financial services for data-driven green innovation enterprises.

Enhance interdisciplinary professional service capabilities: The digital industry has fast technological iteration and complex environmental impacts. Financial institutions need to accelerate the building of interdisciplinary professional teams, strengthen their understanding of digital technology, energy management, and environmental science, and establish and improve a professional assessment, pricing, and risk management capability system for green digital projects to meet the growing market demand.

For digital enterprises: Elevate the strategic positioning of green development: Digital enterprises should view green finance as a strategic opportunity to achieve sustainable development, rather than a simple financing channel. They should fully integrate the ESG concept into the entire process of corporate governance, investment decision-making, supply chain management, and technology research and development, transforming sustainable development from a cost center into a value creation center.

Proactively embrace information transparency: Under increasingly strict regulatory and market requirements, transparent, credible, and high-quality ESG information disclosure is key for enterprises to obtain high-quality capital and win the trust of customers and investors. Digital enterprises should proactively establish and improve their environmental data monitoring and disclosure systems, actively participate in international green standard certification, and build their excellent ESG performance into a core competitive advantage.

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