Digital-Green Technology Integration and the Synergistic Development of Pollution Reduction and Carbon Mitigation: Theoretical Logic, Mechanisms and Implementation Paths

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Abstract: Improving environmental quality while pursuing carbon peaking and carbon neutrality makes the synergistic control of pollution reduction and carbon mitigation a central issue in environmental governance. Through their integration, digital and green technologies are reshaping the technological pathways through which pollutants and greenhouse gases are reduced. Drawing on Schumpeter's notion of "new combinations", synergetic, technology convergence and co-benefits research, this paper defines digital technology, green technology and their integration, and constructs a theoretical framework for understanding how digital-green technology integration affects synergistic pollution reduction and carbon mitigation. The analysis identifies three foundations of integration, namely goal congruence, factor complementarity and data generality, and a three-tier structure progressing from the factor level through the process level to the system level. Integration influences synergistic pollution and carbon reduction through five mechanisms: source reduction, coordinated process control, improved end-of-pipe treatment efficiency, data-driven precision governance, and industrial-chain and spatial spillovers. Its effectiveness remains subject to technological, organizational and institutional constraints, alongside risks from the growing energy use of digital infrastructure and rebound effects associated with efficiency improvements. Accordingly, this paper proposes implementation paths covering technological supply, greener digital infrastructure, collaborative governance institutions, policy instrument innovation, tiered pilot demonstrations and capacity building.

Keywords: Digital Technology; Green Technology; Technology Convergence; Co-Benefits; Synergistic Control of Pollution Reduction and Carbon Mitigation; Mechanism

1. Introduction

The mitigation of climate change and the control of local air pollution have long been treated as two relatively separate policy fields. Recent assessment work by the Intergovernmental Panel on Climate Change indicates that mitigation pathways consistent with the temperature goals of the Paris Agreement can deliver substantial improvements in air quality and human health, and that the systematic consideration of such co-benefits is a prerequisite for sound climate policy design [1]. A growing body of literature has examined the concept, measurement and political economy of climate policy co-benefits, showing that co-benefits in domains such as air quality and health are frequently of the same order of magnitude as mitigation costs, and in some cases even larger, yet are seldom internalized in decision-making [2,3]; related work further indicates that the monetized health benefits of mitigation strategies can be of the same order of magnitude as mitigation costs [4]. Empirical work also demonstrates that tightening conventional air-pollutant controls can generate sizeable carbon co-benefits, which provides direct evidence for the technical feasibility of coordinated governance [5].

The practical foundation of synergistic pollution and carbon reduction lies in the highly homologous nature of environmental pollutants and carbon emissions: both originate predominantly from the extraction and combustion of fossil energy, from the conversion processes of industrial production, and from the operation of end-use and end-of-pipe facilities [4,5]. This homology implies that pollution reduction and carbon mitigation naturally overlap in terms of governance objects, governance links and governance instruments, and it also creates the possibility of

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technological synergy. From the perspective of technological evolution, digitalization and greenization have become the two major transformation trends of the contemporary economy. On the one hand, digital technologies such as artificial intelligence, big data, cloud computing, the Internet of Things, fifth-generation mobile communication and digital twins are diffusing rapidly, and international organizations have documented both their potential to raise energy efficiency and the additional energy demand they create [6,7]. On the other hand, green technologies covering energy efficiency, clean energy supply, deep pollution treatment, carbon capture and resource recycling are continuously iterating, while the convergence of digitalization and sustainability has been identified as a promising yet still contested route towards sustainable development [8].

The academic community has accumulated rich findings on the environmental effects of digitalization. Based on a cross-country cross-industry panel of OECD economies, Schulte et al. [9] find that information and communication technology (ICT) capital is associated with a significant reduction in total energy demand, and that this effect is more pronounced for non-electric than for electric energy. Focusing on a large developing economy, Ren et al. [10] show that internet development raises the scale of energy consumption through economic growth while simultaneously accelerating the decline of energy intensity through structural and technological channels. Javed and Rapposelli [11] uncover asymmetric effects of ICT on carbon dioxide emissions in Western and Eastern European economies, implying that the direction and magnitude of ICT's environmental impact are context dependent rather than universal. Mai et al. [12] find that digital transformation promotes synergistic pollution and carbon reduction in heavily polluting enterprises through internal innovation coordination and external innovation networks. A second strand of literature issues an important warning: Lange et al. [13] argue that, on balance, digitalization tends to increase energy consumption because the direct energy use of the ICT sector and growth effects outweigh efficiency gains; Belkhir and Elmeligi [14] project that the ICT sector's share of global greenhouse gas emissions could grow from roughly 1-1.6% in 2007 to exceed 14% of the 2016-level global total by 2040 if left unchecked; and Hittinger and Jaramillo [15] caution that the net energy effect of the Internet of Things is far less favourable than local savings suggest once remote and embodied energy use are taken into account.

Existing research provides important support for this paper, yet there remains room for extension. First, most studies examine the environmental effects of either digital technology or green technology separately, and rarely characterize the concept, formation mechanism and identification criteria of their deeply coupled form, namely "integration" [9-11]. Second, empirical assessment predominates while theoretical construction is relatively weak: no unified analytical framework has been formed for the internal mechanisms through which integration affects synergistic pollution and carbon reduction [7,8]. Third, insufficient attention has been paid to the conditions under which integration effectiveness is released, to its heterogeneous manifestations across industries and regions, and to the alienation risks created by the growing energy use of digital infrastructure and by rebound effects [13-15]. In view of this, this paper constructs a theoretical analytical framework running through "conceptual definition—theoretical origin—integration mechanism—action mechanism—constraints—implementation paths", and systematically addresses four questions: why digital technology and green technology can be integrated, how they are integrated, through which mechanisms integration affects synergistic pollution and carbon reduction, and under what conditions its effectiveness is released.

2. Conceptual Definition and Theoretical Foundations

2.1 Connotations of Digital Technology and Green Technology

Digital technology is a technological cluster that takes data as the core element and information and communication technology as the foundation, and that reshapes resource allocation through the perception, connection, computation, modelling and optimization of physical systems and socio-economic activities. In terms of composition, it can be divided into four layers: underlying support technologies

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(network communication and computing infrastructure), data element technologies (collection, storage, governance, exchange and trading), intelligent application technologies (artificial intelligence, machine learning and digital twins), and platform integration technologies (industrial internet and cloud platforms) [6,7]. The essential characteristics of digital technology lie in its generality and permeability: it does not directly produce emission reductions, but by lowering the cost of information acquisition, accelerating transmission and changing the mode of information processing, it reduces uncertainty and friction in the operation of economic systems, thereby creating conditions for the effectiveness of other technologies to be released.

Green technology, by contrast, is a general term for technologies aimed at reducing environmental risks, lowering pollutant and greenhouse gas emissions, and improving resource and energy efficiency. Braun and Wield [16] were among the first to define green technology as technologies, processes and products that improve environmental quality by reducing pollution, resource consumption and ecological degradation. In a broader sense, the green economy literature emphasizes that human well-being and environmental protection must be balanced under the constraints of resource and environmental carrying capacity [17], which provides a value reference for the goal orientation of green technologies. Unlike digital technology, green technology directly addresses the material and energy dimensions of environmental problems and has an explicit environmental goal orientation, but its diffusion frequently encounters obstacles such as high costs, long retrofit cycles and strong externality of benefits.

It can be seen that digital technology and green technology are complementary in functional positioning: the former addresses the information and decision-making problems of "invisible, unquantifiable and unmanageable", while the latter addresses the material and energy problems of "irreplaceable, unreducible and untreatable". This functional complementarity constitutes the realistic starting point for the integration of the two.

2.2 Theoretical Basis of Technology Integration

Technology integration is not a simple superposition of two types of technologies, but the recombination and reconfiguration of technological elements at the level of technological trajectories. Schumpeter [18] defined innovation as the "new combination" of productive factors, emphasizing that the recombination of existing elements rather than the creation of entirely new elements is the fundamental driver of economic development. This idea provides the earliest theoretical basis for understanding technology integration: when two technological systems that originally belong to different technological trajectories are introduced into the same production process and undergo functional coupling, they may generate effectiveness exceeding the sum of their separate applications. The theory of synergetics further indicates that nonlinear interactions among subsystems of an open system can produce holistic emergence, the key of which lies in the formation of structured mutual support relationships rather than loose coexistence [19].

The convergence literature provides an operational basis for identifying such recombination. Curran and Leker [20] demonstrate that patent co-classification can be used to monitor the blurring of boundaries between previously distinct technological fields, which offers a measurement approach for identifying digital-green convergence. Meanwhile, the theory of directed technical change shows that when clean and dirty inputs are sufficiently substitutable, properly designed price and research policies can redirect innovation towards clean technologies, implying that environmental goals can be internalized into the direction of technological search [21]. Recent firm-level evidence also links digital-green technology innovation to improved corporate environmental performance, with the effect varying according to organizational and technological conditions [22].

Specifically for digital technology and green technology, the essence of their integration is as follows: taking the data element as the link, the perception, computation and optimization capabilities of digital technology are embedded into the material transformation and pollution reduction processes of green technology, while the environmental goal constraints of green technology are internalized into the

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optimization direction of digital technology operation, thereby forming a closed-loop coupling of "information-material-energy" within the technological system. Accordingly, this paper defines "digital-green technology integration" as an integrated technological form generated by digital technology and green technology through factor embedding, process integration and system coupling across research and development, design, manufacturing, operation management and end-of-life recycling; its identification criterion is whether the two types of technologies form inseparable functional complementarity and iterative co-evolution within the same technological system.

2.3 Connotation of the Synergistic Development of Pollution Reduction and Carbon Mitigation

The theoretical core of synergistic pollution reduction and carbon mitigation is that, building on the homology of environmental pollutants and carbon emissions, the synchronous reduction of both can be pursued within a single governance framework through goal coordination, regional coordination, sectoral coordination, task coordination, policy coordination and regulatory coordination, so that overall governance effectiveness exceeds the sum of separate governance [1-3]. The co-benefits concept systematically elaborated in international climate assessment and in subsequent reviews emphasizes the additional benefits of greenhouse gas mitigation policies for local air quality and human health, and provides an internationally accepted conceptual basis for synergistic governance [1,2,4]. Empirical evidence further shows that air-pollutant control policies produce significant carbon co-benefits, while also revealing lock-in risks when near-term targets are met by expanding fossil-based capacity [5].

It should be noted that synergy is not automatically realized. Jaffe et al. [23] pointed out that environmental technological change confronts two market failures simultaneously: the environmental externality that makes private returns to emission reduction lower than social returns, and the knowledge spillover that makes private returns to innovation lower than social returns. Because pollution reduction is local, short-term and directly beneficial to health, whereas carbon mitigation is global, long-term and indirect in benefits, the two objectively differ in the ranking of governance objectives, in spatiotemporal scale and in the selection of policy instruments, and may even give rise to non-synergistic outcomes such as "pollution reduction with carbon increase" (additional emissions from the energy use of end-of-pipe facilities) or "carbon mitigation with pollution increase" (secondary pollution generated by certain technological substitutions). Therefore, exploring technological paths that can enhance both types of effectiveness simultaneously has become a common concern of theory and policy, and digital-green technology integration is precisely the key path carrying this expectation.

3. The Internal Mechanism of Digital-Green Technology Integration

3.1 Three Foundations of Integration

3.1.1 Goal congruence

The economic goal of digital technology lies in efficiency improvement and cost reduction, while the environmental goal of green technology lies in emission reduction and resource conservation; the two are highly consistent in the direction of efficiency improvement, namely creating more output with less resource input. The decline in energy and material consumption per unit of output is both the result of digital optimization and the result of green substitution, which endows the integration of the two types of technologies with endogenous goal consistency [7,9].

3.1.2 Factor complementarity

Green technology provides the means of transformation at the material and energy levels (clean energy substitution, process reconstruction, end-of-pipe purification and recycling), while digital technology provides the means of perception and decision-making at the information level (real-time monitoring, model prediction, parameter optimization and coordinated scheduling). The former is the "hard" technological carrier, while the latter is the "soft" technological empowerment; the two are complementary rather than substitutive in the input structure, and their integration can form a composite capability of "hard technology plus soft empowerment".

3.1.3 Data generality

As a production factor, data is replicable and shareable and exhibits diminishing marginal cost, which enables it to penetrate the interface

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barriers between different technological systems and to serve as a universal medium connecting digital technology and green technology [6]. The interconnection of energy consumption data, emission data, process parameter data and material flow data allows the previously separate tasks of energy conservation, emission reduction and pollution treatment to be optimized within a unified data space, which is the technological prerequisite for integration to occur.

3.2 The Three-Tier Structure of Integration

Based on differences in the depth of integration, digital-green technology integration can be divided into three progressively advancing levels.

3.2.1 Factor-level integration

Its main manifestation is the embedding of data elements and green technology elements into a single device or process step, such as installing intelligent sensors and variable-frequency control systems on motors, boilers and fans, and configuring online monitoring and automatic dosing devices for pollution treatment facilities. This level of integration has a low threshold and quick results, but its scope of action is limited to local areas, and the release of effectiveness is limited.

3.2.2 Process-level integration

Its main manifestation is that digital technology runs through the entire life cycle of research and design, raw material procurement, production and manufacturing, logistics and warehousing, product use and recycling, forming integrated optimization oriented towards environmental performance. Typical forms include: process parameter optimization based on digital twins, enabling combustion, reaction and separation processes to achieve simultaneous optimization of efficiency and emissions; green design based on life cycle assessment and product digital passports, reducing material consumption and end-of-pipe disposal pressure from the source; and energy management systems based on intelligent scheduling, realizing multi-energy complementarity and demand-side response [7]. The core of process-level integration lies in breaking the information silos between process steps and extending local optimization to whole-process optimization.

3.2.3 System-level integration

Its main manifestation is that the scope of integration extends from a single enterprise to industrial parks, industrial chains and regions, forming a technology-organization composite system with multi-agent and multi-scale coupling. Typical forms include: industrial-chain coordinated carbon reduction supported by industrial internet platforms; circular transformation characterized by the integrated optimization of energy flows, material flows and information flows within industrial parks; and multi-source data fusion platforms oriented towards regional environmental quality improvement and carbon peaking targets [6,8]. System-level integration can produce significant spillover and network effects, and represents the advanced form through which synergistic effectiveness is released.

The above three levels are not mutually substitutive; rather, they form a progressive relationship from point to area and from shallow to deep. Enterprises often deepen integration gradually along the path of "factor level—process level—system level", and differences in the level attained also explain the differentiation of governance effectiveness among different actors.

3.3 Dynamic Evolution and Identification Criteria of Integration

From a dynamic perspective, digital-green technology integration roughly goes through four stages: technology identification, adaptive transformation, integrated application and iterative diffusion. The technology identification stage addresses the question of whether applicable technologies exist; the adaptive transformation stage addresses whether the technologies can match existing processes and equipment; the integrated application stage addresses whether multiple technologies can operate in coordination; and the iterative diffusion stage addresses whether the integration scheme can be replicated on a large scale. The four stages constitute a positive feedback loop of "integration—learning—reintegration": with data accumulation and algorithm improvement, the depth and breadth of integration continue to increase [20].

In terms of identification criteria, it is necessary to distinguish three easily confused technological combination states. The first is technology coexistence, in which the two types of technologies are applied independently within the same actor without functional

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coupling. The second is technology coordination, in which the two types of technologies support each other in a loosely coupled manner but have not formed a unified system architecture. The third is technology integration, in which the two types of technologies are deeply coupled at the level of system architecture, producing inseparable overall functions and emergent effectiveness. The patent co-classification approach proposed in the convergence literature offers an operational tool for distinguishing these states [20]. The "integration" discussed in this paper specifically refers to the third state.

4. Mechanisms through Which Digital-Green Technology Integration Affects the Synergistic Development of Pollution Reduction and Carbon Mitigation

On the basis of the above analysis, this paper summarizes the mechanisms through which digital-green technology integration affects the synergistic development of pollution reduction and carbon mitigation into five positive mechanisms and one constraining reverse mechanism. City-level evidence indicates that industrial digitization promotes synergistic pollution and carbon reduction through renewable energy substitution, green process innovation and environmental regulation, while also producing positive spatial spillovers [24].

4.1 Source Reduction Mechanism: Energy Structure Optimization and Energy Efficiency Improvement

Source reduction is the most synergistic pathway of pollution and carbon reduction, whose mechanism lies in simultaneously reducing pollutants and carbon emissions by cutting fossil energy consumption. The role of digital-green technology integration in this link is manifested in two aspects. On the one hand, through panoramic perception and load forecasting of energy-using systems, digital technology supports the high-proportion accommodation of clean energy and multi-energy complementary scheduling, including the coordinated operation of distributed photovoltaics and storage, park-level "source-grid-load-storage" integrated optimization, demand-side response and energy efficiency diagnosis, thereby alleviating the accommodation constraints caused by renewable energy volatility and creating conditions for the large-scale application of green energy technologies [7]. On the other hand, the integrated system disaggregates energy consumption and emission data to the equipment and process levels, enabling energy efficiency benchmarking and dynamic optimization, and transforming extensive energy management into refined real-time control. Empirical evidence that ICT capital reduces total and non-electric energy demand, and that internet development accelerates the decline of energy intensity, corroborates this theoretical judgement [9,10].

4.2 Coordinated Process Control Mechanism: Process Reconstruction and Coordinated Control of Multiple Pollutants and Greenhouse Gases

Industrial processes are the common source of pollutants and carbon emissions, so coordinated control at the process level is of decisive significance. Digital-green technology integration operates through three paths. First, with the help of advanced process control, machine vision and digital twins, real-time optimization of key parameters such as combustion temperature, air-fuel ratio, reaction residence time and material ratio enables a single process adjustment to simultaneously suppress the formation of pollutants such as nitrogen oxides and volatile organic compounds and to reduce fuel consumption, achieving "same parameter, dual reduction" [7]. Second, combining process-route reconstruction technologies (short-process steelmaking, raw material and fuel substitution, use of recycled metals) with digital production scheduling and quality control systems reduces quality fluctuations and cost risks during reconstruction, promoting the diffusion of clean processes. Evidence from the directed technical change literature indicates that once the direction of innovation is redirected towards clean inputs, the cost of clean technology declines along the learning curve, which provides a theoretical basis for the economic feasibility of coordinated control [21]. Third, coupling end-of-pipe carbon reduction technologies such as carbon capture, utilization and storage with intelligent monitoring and regulation technologies reduces capture energy consumption and operating costs, alleviating the negative effect of "carbon mitigation with energy increase".

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4.3 Efficiency Improvement Mechanism of End-of-Pipe Treatment: Intelligent Treatment Facilities and Pollution Reduction without Carbon Increase

End-of-pipe treatment is an important link in pollution prevention and control, but the electricity and chemical consumption of treatment facilities, as well as the upstream production of treatment chemicals, generate indirect carbon emissions. If treatment intensity increases while treatment efficiency remains unchanged, the non-synergistic outcome of "pollution reduction with carbon increase" may arise [5]. The response logic of digital-green technology integration is to improve treatment efficiency through intelligent means. Through the closed loop of "online monitoring—model prediction—automatic control", precise dosing is realized in aeration, chemical dosing, spraying and denitration agent injection, reducing resource waste and energy consumption caused by overdosing. Through equipment energy efficiency diagnosis and intelligent operation and maintenance, the operating efficiency of energy-intensive auxiliary equipment such as fans, pumps and induced draft fans is improved. Through the coupling of green technologies such as sludge biogas cogeneration, water source heat pumps and on-site photovoltaic generation with intelligent control, the energy self-sufficiency of facilities such as wastewater treatment plants is enhanced [7]. These pathways make it possible to raise treatment intensity while keeping the carbon footprint of treatment roughly stable or even declining.

4.4 Data-Driven Precision Governance Mechanism: From Experience-Based Governance to Collaborative Governance

Differences in governance effectiveness arise not only from technological means but also from decision-making methods. The reshaping of the governance system by digital-green technology integration is manifested in four transformations. First, the monitoring system evolves from separation to integration: through the connection of integrated monitoring networks with emission source surveys and accounting verification systems, the synchronous collection and cross-verification of pollutant and greenhouse gas emission data are promoted [1]. Second, the accounting system evolves from rough to precise: with the help of the Internet of Things and distributed ledger technologies, the traceability and credibility of emission data are enhanced, reducing the interference of accounting uncertainty in collaborative decision-making [6]. Third, the regulatory approach evolves from passive to proactive: based on anomaly identification and early warning through multi-source data fusion, supervision is extended from end-of-pipe enforcement to process control. Fourth, the information environment evolves from closed to transparent: improvements in the quality of environmental information disclosure strengthen external supervision and improve the information basis of market mechanisms such as green finance and green procurement [8]. In addition, the coordination of pollutant discharge permitting and carbon emission management in terms of control requirements, self-monitoring and record-keeping also requires a unified data foundation, which likewise depends on technological integration [2].

4.5 Industrial Chain Coordination and Spatial Spillover Mechanism: Effectiveness Diffusion from Points to Areas

Synergistic pollution and carbon reduction is systemic and spatially correlated; improvement in a single enterprise or link alone can hardly achieve overall optimization. The spillover mechanism of digital-green technology integration can be understood at three scales. At the enterprise level, the productivity gains and green innovation generated by integration can be transmitted along the supply chain, since digital technologies reduce coordination costs between upstream and downstream firms and allow environmental performance requirements to be passed through procurement standards [6,9]. At the industrial park and industrial chain level, industrial internet platforms and park-level energy-carbon management systems open up material flows, energy flows and information flows between enterprises, promoting symbiotic arrangements such as cascade utilization of waste heat and pressure, water reuse and by-product exchange, so that the "waste" of one enterprise becomes the "raw material" of another. At the regional level, joint prevention and control and coordinated scheduling based on a unified data platform help alleviate the cross-boundary transmission of air pollutants, and provide technical support for linking market mechanisms such as carbon markets and

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emission trading schemes [7,8].

4.6 Constraining Reverse Mechanism: Alienation Risks and Rebound Effects

It must be soberly recognized that digital-green technology integration does not necessarily lead to synergistic gains, and several reverse forces exist in the process of releasing its effectiveness. First, the growth of energy use by digital infrastructure itself. The electricity consumption of data centres, base stations and computing facilities rises rapidly with digital transformation, and if the power supply remains fossil-dominated, digitalization may itself generate additional emissions [13-15]. Second, the rebound effect of efficiency improvement. Improvements in energy efficiency reduce effective costs and induce expansion of output and service demand, which may partially or even fully offset the emission reductions achieved, a phenomenon discussed extensively as the Jevons paradox [25]. Firm-level evidence shows that digital technology innovation can reduce carbon emissions while also generating an energy rebound effect that partially offsets these reductions [26]. Third, technology lock-in and path dependence. The deep binding of existing process equipment with specific digital systems may create a new form of lock-in that delays the adoption of more radical green technologies [5]. Fourth, data silos and security constraints. Unclear data ownership, missing interface standards and insufficient sharing incentives may keep integration at the factor level and prevent it from deepening towards the system level [6]. Identifying these reverse mechanisms is a prerequisite for designing effective policies.

5. Constraints and Heterogeneity Analysis of Integration Effectiveness

5.1 Constraints at the Technological Level

First, technological maturity mismatch. Some key links of green technology, such as low-cost carbon capture, hydrogen-based metallurgy and long-duration energy storage, remain at an early stage of engineering verification or commercialization; although digital technology is relatively mature, it still lacks highly reliable models and high-quality data adapted to industrial scenarios, and the maturity gap between the two limits the depth of integration [7]. Second, missing interfaces and standards. Inconsistent equipment communication protocols, data formats and emission accounting conventions raise the cost of system integration, which particularly constrains small and medium-sized enterprises [20]. Third, insufficient data quality. The completeness, continuity and accuracy of industrial field data are often inadequate, weakening the credibility of model prediction and optimization [6].

5.2 Constraints at the Organizational Level

From the perspective of investment, integration is characterized by high upfront sunk costs, long payback periods and environmental benefits that are difficult to appropriate; where environmental costs are not fully internalized, firms lack investment incentives [23]. From the perspective of capability, the supply of interdisciplinary talent who simultaneously master process engineering, environmental engineering and digital technology is in shortage, leading to the situation of "having technologies but not knowing how to use them, and having systems but not using them well" [6]. From the perspective of management, integration often requires synchronous changes in organizational structure, assessment systems and business processes, and organizational inertia constitutes hidden resistance [8].

5.3 Constraints at the Institutional Level

In terms of departmental division of labour, digitalization and greenization usually belong to different policy domains with distinct goal systems, performance indicators and funding channels, so policy coordination needs to be strengthened [2]. In terms of accounting systems, the statistical conventions, reporting boundaries and verification rules for pollutants and greenhouse gases have not been fully unified, which affects the scientific assessment of synergy. In terms of market mechanisms, the linkage among carbon markets, emission trading, green power trading and energy-use rights trading remains insufficient, and the price signalling of environmental externalities is incomplete [1]. In terms of regulatory intensity, differences in environmental regulation across jurisdictions affect firms' pressure and motivation to adopt integrated technologies; the literature on competitiveness and environmental regulation suggests that well-designed regulation can trigger innovation offsets, but that such offsets are conditional on instrument

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design and firm capabilities [27].

5.4 Heterogeneity Manifestations

Theoretically, the synergistic effect of digital-green technology integration is heterogeneous along four dimensions. Industry heterogeneity: industries with complex process flows, high emission intensity and good digital foundations, such as electric power, steel, petrochemicals and building materials, offer greater space for integration, whereas industries with simple processes and dispersed emission sources have limited marginal benefits [7,9]. Regional heterogeneity: differences in digital infrastructure, industrial structure, energy endowment and regulatory intensity determine the starting point and returns of integration, which is consistent with evidence that the effects of ICT on emissions are asymmetric across economies [11]. Enterprise heterogeneity: large, innovation-intensive and fast-growing firms have advantages in capital, talent and risk-bearing capacity, making it easier for them to cross the integration threshold, whereas small and medium-sized enterprises face a triple dilemma of not knowing how, being unable to afford, and not daring to transform [6]. Stage heterogeneity: the relationship between digital investment and environmental performance may be nonlinear, showing a pattern of short-term cost pressure followed by longer-term gains; during the investment phase, infrastructure and factor costs may temporarily obscure or even negate the synergistic effect [10], which implies that policy design should be stage-adaptive and should not prematurely deny the value of integration. Zhao et al. [28] identify a U-shaped relationship between digital technology innovation and urban synergistic pollution and carbon reduction, indicating that the effect can shift from inhibition to promotion as innovation develops.

6. Implementation Paths and Policy Recommendations

The central policy lesson of the co-benefits literature is that climate and environmental objectives should be integrated in a single governance framework rather than pursued separately, and that digitalization should be deliberately steered towards sustainability rather than assumed to be beneficial by default [1-3,8]. Centred on this lesson, this paper proposes six implementation paths.

6.1 Strengthening the Technological Supply for Digital-Green Integration

Around the common technological needs of pollution and carbon reduction in key industries, a set of integrated research directions should be prioritized: digital twins and advanced process control for process optimization, intelligent equipment for coordinated control of multiple pollutants and greenhouse gases, energy-carbon management platforms for parks and industrial chains, and intelligent monitoring and regulation technologies for carbon capture, utilization and storage. In terms of organization, leading firms should be encouraged to form innovation consortia that open up the "process—equipment—software—data" innovation chain. In terms of basic support, the formulation of key standards for equipment interconnection, data interfaces and emission accounting should be accelerated in order to reduce system integration costs [20]. At the same time, public support for clean research and development should be strengthened, since evidence on induced innovation shows that both energy prices and directed research subsidies measurably shift the direction of inventive activity towards energy-saving and clean technologies [21,29].

6.2 Promoting the Greening of Digital Infrastructure Itself

The key to preventing "pollution reduction with carbon increase" is to make computing power and networks themselves green. First, the spatial layout of new digital infrastructure such as data centres and base stations should be coordinated with renewable energy availability, guiding capacity towards regions with abundant clean power [7]. Second, energy efficiency constraints such as power usage effectiveness should be strictly enforced, and energy-saving technologies including liquid cooling, waste heat recovery and intelligent sleep modes should be promoted [14]. Third, digital infrastructure should be incorporated into carbon accounting and energy conservation supervision, and large digital technology firms should be encouraged to adopt and disclose low-carbon development plans, so that the greening of the digital industry drives coordination along the whole chain [13,15].

6.3 Improving Collaborative Governance

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Institutions with Integrated Planning and Implementation

Institutional integration needs to be advanced with the support of technological integration. First, greenhouse gas assessment should be incorporated into environmental impact assessment of plans and projects, so that the pollutant and carbon implications of new emission sources are evaluated simultaneously and technological pathways are optimized jointly [1]. Second, pollutant discharge permitting can be used as the carrier for coordinating pollutant and carbon management, achieving integration in permit conditions, self-monitoring, record-keeping and information reporting [2]. Third, an evaluation system for the degree of synergy between pollution reduction and carbon mitigation should be established and applied to identify non-synergistic areas and links, providing a basis for dynamically adjusting governance priorities [3,5]. Fourth, monitoring, accounting and verification systems for pollutants and greenhouse gases should be interconnected to form a unified data foundation [6].

6.4 Innovating Policy Instruments with Incentives and Constraints

On the incentive side, green finance and transition finance instruments should be used to channel funds towards integrated technological retrofits, and green product certification and public procurement should be improved to expand the market demand for integrated solutions [8]. On the constraint side, environmental taxes, resource taxes and differentiated electricity pricing should be improved so that environmental costs are more fully internalized, and the rules of carbon markets, emission trading schemes and energy-use rights trading should be aligned to avoid duplicate costs or regulatory gaps [23]. On the design side, the experience with innovation offsets suggests that flexible, market-based and predictable instruments are more conducive to inducing clean technological change than rigid command-and-control mandates [27]. On the capacity side, public services supporting the digital transformation of small and medium-sized enterprises should be expanded through industrial internet platforms, sector-level solutions and diagnostic services [6].

6.5 Conducting Hierarchical and Classified Pilot Demonstrations

Collaborative innovation pilots should be promoted at four levels: region, city, industrial park and enterprise. At the regional level, the focus is on combining structural adjustment, technological innovation and institutional innovation. At the city level, the focus is on coordinated advancement mechanisms adapted to different city types. At the industrial park level, the focus is on institutional innovation for intensive, economical and circular use of energy and resources. At the enterprise level, the focus is on advanced technologies for coordinated reduction of multiple pollutants and greenhouse gases and on building near-zero emission benchmark enterprises [7]. Because digitalization and sustainability are still loosely coupled in practice, pilots should be systematically evaluated so that replicable experience can be accumulated regarding the greening of the digital industry, the dual transformation of traditional industries, low-carbon urban governance and the design of policy mechanisms [8,15].

6.6 Strengthening Capacity Building and Risk Prevention

First, the cultivation of interdisciplinary talent should be strengthened by aligning engineering education and vocational training with industrial demand, so as to alleviate the structural mismatch between process knowledge and data competence [6]. Second, data security and hierarchical classification systems should be improved to enhance data availability while protecting commercial secrets and privacy, thereby breaking data silos [7]. Third, a dynamic evaluation and correction mechanism for integration effectiveness should be established, with particular attention to rebound effects and output expansion induced by efficiency improvement, so that technological progress is not offset by scale expansion [25]. Fourth, attention should be paid to the digital divide between regions and firms; infrastructure extension, public service provision and targeted fiscal transfers can prevent integration dividends from concentrating in a few actors and aggravating development imbalance [6,11].

7. Conclusion and Outlook

Focusing on the impact of digital-green technology integration on the synergistic

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development of pollution reduction and carbon mitigation, this paper conducts a theoretical analysis and draws the following conclusions.

First, digital-green technology integration is a key form through which the traditional technological path of pollution and carbon reduction can be broken through. Digital technology addresses perception and decision-making problems at the information level, while green technology addresses substitution and reduction problems at the material and energy levels. The two possess endogenous conditions for integration on the triple foundations of goal congruence, factor complementarity and data generality, and they progress sequentially along the factor level, the process level and the system level, ultimately producing emergent effectiveness that exceeds technology coexistence and simple coordination.

Second, integration acts on synergistic pollution and carbon reduction through five mechanisms. The source reduction mechanism centres on energy structure optimization and energy efficiency improvement; the coordinated process control mechanism centres on process parameter optimization and coordinated control of multiple pollutants and greenhouse gases; the end-of-pipe treatment efficiency improvement mechanism centres on the intelligent operation of treatment facilities and the reduction of energy and chemical consumption; the data-driven precision governance mechanism centres on the integration of monitoring and accounting and on information transparency; and the industrial-chain and spatial spillover mechanism centres on supply chain transmission, park symbiosis and regional coordination. The five mechanisms act on different links of the emission chain and jointly constitute the technological support for whole-process coordination.

Third, the release of integration effectiveness is conditional and heterogeneous. Technological maturity, interface standards and data quality constitute technological constraints; cost-benefit structures and organizational capabilities constitute organizational constraints; and departmental division, accounting conventions and the linkage of market mechanisms constitute institutional constraints. Meanwhile, reverse forces such as the growing energy use of digital infrastructure, the rebound effect of efficiency improvement, technology lock-in and data silos may weaken the synergistic effect. The integration effect displays clear heterogeneity along the four dimensions of industry, region, enterprise and stage, and policy design should reflect both differentiation and stage adaptability.

The main limitation of this paper is that, as a theoretical study, the proposed mechanism framework still needs empirical testing and case verification. The measurement of the degree of digital-green technology integration, the quantitative decomposition of integration effectiveness, and the comparison of the relative importance of different mechanisms all await further research. Future work can be expanded in three directions: first, constructing a measurement index for digital-green technology integration at the enterprise or park level, for instance by drawing on patent co-classification methods , so as to provide a tool for empirical research; second, selecting typical industries for case studies to test the action mechanisms and constraints proposed here; and third, conducting policy evaluation research to quantify the actual effects of combining collaborative governance institutions with policy instruments, thereby providing a basis for optimizing policy design.

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