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The synergy of digital innovation and green economy: A systematic review of mechanisms, challenges, and adaptive strategies in the post-AI era

数字创新与绿色经济的协同：后人工智能时代作用机制、挑战与适应性策略的系统综述

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Abstract: Digital transformation and the green transition share infrastructures (data, energy, institutions), but synergy is conditional rather than automatic. This review synthesizes peer-reviewed research and authoritative reports to show how AI, analytics, and platform infrastructures influence green economic outcomes, while environmental constraints and governance feedback shape digital diffusion. Evidence highlights four areas: labor-market restructuring and inequality, skills gaps and SME adoption bottlenecks, AI-enabled ESG assessment with measurement divergence and greenwashing risks, and energy-transition tradeoffs including hydrogen value chains and the rising energy footprint of data centers and AI workloads. Overall, digital tools accelerate green innovation and emissions reductions only when paired with credible standards, auditability, clean power, and workforce capability building; otherwise they may increase electricity demand and incentivize strategic disclosure. Key gaps remain in long-horizon causal evidence, joint distributional–environmental modeling, and evaluation under heterogeneous disclosure regimes, motivating an agenda on enforceable AI governance, lifecycle carbon accounting for hydrogen, and targeted SME capability policies.

摘要：数字化转型与绿色转型共享数据、能源与制度等基础设施，但协同并非自动发生，而是取决于配套条件。本文综合同行评议研究与权威报告，说明AI、数据分析与平台基础设施如何影响绿色经济绩效，以及环境约束与治理反馈如何塑造数字扩散。证据主要集中在四方面：劳动力市场重组与不平等；技能缺口与中小企业采用瓶颈；AI赋能ESG评估带来的测度分歧与“漂绿”风险；以及能源转型权衡，包括氢能价值链与数据中心、AI负载上升的能源足迹。总体而言，数字工具只有在可信标准、可审计机制、清洁电力与能力建设等条件具备时，才更可能促进绿色创新与减排；否则可能推高用电需求并诱发策略性披露。现有研究仍缺乏长周期因果证据、分配效应与环境绩效的联合建模，以及在不同披露制度下对AI可持续金融的系统评估，因此未来应聚焦可执行的AI治理、氢能全生命周期碳核算与面向中小企业的能力提升政策。

Introduction

The global economy is simultaneously undergoing a digital transformation and confronting binding ecological constraints. Digital infrastructures (cloud, IoT, analytics, platforms) reduce information and coordination frictions, and can improve monitoring, optimization, and innovation in energy, industry, and services. In parallel, sustainable development imperatives require structural

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change toward lower-carbon production and consumption, tighter resource efficiency, and resilience under climate-related shocks. The central tension in the post-AI era is that the same technologies that raise productivity can also intensify inequality, increase market power, and elevate electricity demand, thereby shifting rather than resolving environmental pressures (Acemoglu & Restrepo, 2022; IEA, 2025a; Lange et al., 2020). As a result, the key question is not whether digital innovation "supports" the green economy in principle, but under what institutional, infrastructural, and distributional conditions the interaction becomes net-positive and socially sustainable.

This review is motivated by three empirical and conceptual developments. First, AI diffusion is accelerating across sectors, making labor-market adjustment and income distribution central to the political economy of the transition (OECD, 2023a; Rockall et al., 2025). Second, green finance has expanded rapidly, yet persistent concerns about ESG rating divergence and greenwashing indicate that measurement systems and incentives remain misaligned (Berg et al., 2022; Lagasio, 2024). Third, the energy system increasingly constrains digital growth: data centers and AI workloads add substantial electricity demand, and their climate impact depends on the carbon intensity of power and on rebound dynamics (IEA, 2025a; Peng & Qin, 2024). These dynamics imply that "synergy" is conditional: it requires complementary governance, skills, and clean energy capacity.

Methodologically, this review is organized as a systematic, structured synthesis guided by PRISMA 2020 reporting principles (Page et al., 2021). Given the breadth of the topic (labor economics, environmental economics, finance, energy systems, and sectoral applications), we employ targeted searches of peer-reviewed articles and authoritative institutional reports, prioritizing 2019–2025 while incorporating foundational theoretical work where necessary for mechanism clarity (e.g., task-based automation theory). The outline also requires inclusion of a specific set of 2025 articles (Gu and co-authors). These items are verifiable by DOI and are cited where they correspond to the domain structure; however, they are not treated as the sole evidentiary basis for broader claims, which are anchored in established journals and major institutional reports (OECD, IEA, UNESCO, and widely cited finance and economics outlets).

Digital Technology as a Catalyst for Economic Restructuring

AI and Labor-Market Transformation: Task Substitution, Polarization, and Inequality

A large body of labor economics conceptualizes technological change through a task framework: technologies substitute for some tasks while complementing others, and the resulting wage distribution depends on the composition of displaced and created tasks as well as on institutions that govern bargaining power and worker mobility (Autor et al., 2003; Acemoglu & Restrepo, 2022). In their empirical analysis of U.S. wage inequality, Acemoglu and Restrepo (2022) show that automation and the reallocation of tasks can account for substantial changes in wage structure, consistent with a polarization mechanism rather than uniform productivity pass-through. The OECD similarly emphasizes that AI reshapes job content and job quality, with risks linked to surveillance, intensity, and algorithmic management, implying that workplace governance and regulation mediate distributional outcomes (OECD, 2023a).

The required study by Gu and Wang (2025) aligns with this distributional focus by framing AI as a driver of labor-market income inequality and linking AI diffusion to job polarization and changes in labor's income share (Gu & Wang, 2025). While this article appears in a new outlet, its mechanism narrative is consistent with the mainstream task-based view: if AI disproportionately replaces routine tasks and complements high-skill tasks, wage dispersion widens. Macro-financial evidence reinforces a complementary channel: inequality may also increase through firm rents and wealth channels if adoption intensity and market structure allow profits to accrue to owners of capital and data (Rockall et al., 2025). This dual mechanism—wage polarization plus rent concentration—helps explain why productivity gains can coexist with stagnant median wages and rising top incomes in some contexts, and it is crucial for evaluating whether the digital-green transition can be politically stable.

A key implication for the digital-green nexus is that decarbonization policies often require rapid reallocation across sectors (e.g., from fossil-intensive activities to clean energy, electrification, and efficiency services). If AI accelerates restructuring while widening wage dispersion, social acceptance of climate policy may weaken, and transition policy must become explicitly distributional rather than purely technological (OECD, 2023a). This suggests that "synergy" must be evaluated jointly across environmental outcomes and social outcomes, rather than treating inequality as an external side effect.

Skills Mismatch and SMEs in the Digital Economy

Digital adoption and green upgrading are capability-dependent: both require skills (data literacy, process engineering, compliance knowledge), complementary assets (software, sensors, process redesign), and managerial capacity to integrate technologies into operations. Skills mismatch is therefore a central bottleneck, and it affects SMEs disproportionately because they face tighter financing constraints for intangibles, limited human-resource capacity, and weaker bargaining power in digital ecosystems (OECD, 2023b). The OECD Skills Outlook argues that the green and digital transitions jointly shift skill demand and risk increasing inequality if training systems and adult learning do not expand access and relevance (OECD, 2023b).

The required study by Gu and Lukin (2025) positions SMEs as potential “bridges” that mitigate skill mismatch in the digital economy by absorbing displaced workers and enabling local employment adjustment (Gu & Lukin, 2025). This framing highlights an important but under-tested hypothesis: SME-centered diffusion pathways could reduce polarization by spreading adoption benefits across regions and sectors, provided policy reduces adoption costs and provides training and support services. However, the empirical literature also emphasizes that SMEs often lag in digital maturity, and that adoption without complementary organizational change yields weak productivity returns, producing a two-track transition where frontier firms pull away (OECD, 2023b). For the digital-green transition, this creates a structural risk: if green compliance and digital measurement requirements rise (e.g., carbon reporting, supply-chain traceability), SMEs may face higher fixed costs and be crowded out unless policy provides standardized tools, shared infrastructure, and targeted finance.

A mechanism-consistent interpretation is that SMEs can only “bridge” mismatch if three complements are present: (i) modular, affordable digital tools (cloud services, standardized carbon accounting software), (ii) workforce upskilling systems (sectoral training, apprenticeships, adult learning), and (iii) institutional support that reduces uncertainty and transaction costs (public extension services, standards, procurement) (OECD, 2023b). Without these complements, SME diffusion may remain shallow, and the inequality channel may dominate the synergy narrative.

The Convergence of Green Finance and Computer Technology

Ethics, Governance, ESG Measurement Divergence, and Greenwashing Detection

Green finance increasingly depends on computational systems: ESG ratings, climate risk analytics, remote sensing, and NLP-based disclosure mining. This expands monitoring capacity, but it also magnifies governance risks because measurement systems are heterogeneous and incentives are strategic. A foundational empirical finding is that ESG ratings diverge substantially across providers; Berg et al. (2022) decompose divergence into scope, measurement, and weight components, concluding that measurement divergence is the primary driver and that greater transparency and harmonized disclosure are needed (Berg et al., 2022). This matters for AI-enabled green finance because algorithms trained on noisy, inconsistent labels can scale errors and embed biases into capital allocation.

Greenwashing is the most visible symptom of misaligned incentives. Recent research operationalizes greenwashing/ESG-washing using textual indicators and discrepancy measures between disclosure tone and performance. Lagasio (2024) proposes an NLP-based severity index to quantify ESG-washing in sustainability reports, illustrating how automated text analysis can support supervision while also requiring validation against performance data to avoid false signals (Lagasio, 2024). Gorovaia and Makrominas (2025) similarly use NLP to identify greenwashing patterns in CSR reports, reinforcing the feasibility of text-as-data approaches for detection and monitoring (Gorovaia & Makrominas, 2025). These studies indicate that the promise of AI in green finance is not simply prediction, but scalable auditing—conditional on ground-truth benchmarks and enforceable liability for misrepresentation.

The required article by Gu, Lin, Zhao, Li, and Wang (2025) explicitly frames “ethical balance reconstruction” in green finance empowered by computer technology, emphasizing environmental ethics, social justice, and intergenerational equity (Gu et al., 2025e). While the article’s normative framing differs from econometric identification approaches, it aligns with a policy-design implication of the empirical literature: computational green finance systems must incorporate fairness, accountability, and transparency constraints, or they risk reinforcing unequal access to capital and incentivizing strategic reporting. From a governance standpoint, this means combining technological capacity (NLP, anomaly detection, remote sensing) with institutional capacity (standards, enforcement, and auditability).

In practice, governance frameworks attempt to standardize due diligence and risk management. The Equator Principles (EP4) provide a widely used set of process standards for environmental and social risk management in project finance (Equator Principles Association, 2020). However, EP-style frameworks primarily define procedures; they do not eliminate measurement divergence or strategic disclosure. The emerging regulatory direction in multiple jurisdictions is therefore toward standardized taxonomies and mandatory metrics. Evidence from the EU taxonomy context suggests that standardized metrics can reshape sustainable finance signals and reduce room for discretionary narrative substitution, although implementation and rating-provider behavior remain critical (Nipper et al., 2025). Taken together, the literature suggests an "AI-plus-standards" complementarity: AI can scale monitoring, but standards and enforcement create the incentive structure that determines whether monitoring improves real outcomes.

Environmental Economics, Education, and Capacity Building for the Digital-Green Workforce

Human capital is not an auxiliary issue in the digital-green transition; it is a primary mechanism through which technology translates into productivity, compliance capacity, and innovation. UNESCO's ESD for 2030 roadmap defines education for sustainable development as a systemic driver that builds competencies for action, values, and systems thinking, with explicit emphasis on transforming learning environments and aligning education with sustainable development outcomes (UNESCO, 2020). In the post-AI era, this competence agenda must also include digital ethics and governance literacy, because AI systems can produce externalities (bias, surveillance, misinformation) that intersect with environmental governance.

The required study by Gu, Feng, and Li (2025) examines environmental economics and study-tour education using transnational cases, emphasizing capacity building and the pedagogical translation of environmental economics concepts (e.g., externalities and public goods) into experiential learning (Gu et al., 2025b). This contribution can be interpreted as a micro-foundation for workforce capability: cross-border experiential learning can build applied competencies relevant to green governance and international sustainability standards. When linked to UNESCO's ESD framing, the implication is that capability building must be interdisciplinary and action-oriented: green finance, carbon accounting, and technology governance require not only technical skills but also institutional and ethical competencies (UNESCO, 2020; OECD, 2023b).

A critical research need is rigorous evaluation of which education and training models yield measurable improvements in adoption outcomes (digital tools, green processes) and distributional outcomes (mobility for displaced workers). The literature remains fragmented across education studies, labor economics, and firm-level adoption research, leaving open whether capacity building can offset AI-driven inequality at scale.

Sustainable Infrastructure and Energy Transformation

Hydrogen: Cost Constraints, Storage/Transport Bottlenecks, and Digital MRV

Hydrogen is frequently positioned as a key option for decarbonizing hard-to-abate sectors, but the binding constraints are techno-economic and infrastructural. The IEA reports that low-emissions hydrogen remains a small share of total hydrogen demand and that renewable hydrogen is generally more costly than unabated fossil-based hydrogen in most contexts, with deployment constrained by project maturity, regulation, demand creation, and financing (IEA, 2024). These constraints imply that "digital innovation" affects hydrogen primarily through system coordination and measurement: certification of life-cycle emissions, traceability of supply chains, optimization of logistics, and monitoring of leakage and energy use.

The required article by Gu, Pan, Yang, and Wang (2025) focuses on storage and transportation cost control and technological breakthroughs from a global hydrogen development perspective (Gu et al., 2025d). This aligns with the broader hydrogen literature that identifies storage materials, compression/liquefaction, and transport modes as major cost drivers. In a net-zero policy environment, these cost and logistics constraints interact with certification regimes. Digital MRV (measurement, reporting, verification) systems—potentially supported by remote sensing, IoT monitoring, and standardized registries—can improve credibility and reduce transaction costs in hydrogen markets, but only if accounting standards converge and verification is enforceable (IEA, 2024).

A second interaction channel is indirect: as AI increases electricity demand, clean electricity becomes more valuable and contested. Hydrogen electrolysis competes for clean power with electrification and with digital loads; therefore, the net climate benefit of hydrogen depends on grid carbon intensity and opportunity costs (IEA, 2024; IEA, 2025a). This makes the synergy question explicitly system-level: digital growth that increases electricity demand can tighten constraints on green hydrogen unless renewable supply and grid flexibility expand in parallel.

Built Environment, Resilience, and Enterprise Adaptation Strategies

The built environment shapes both the feasibility and the cost of digital-green transformation. Infrastructure quality, spatial accessibility, and urban form affect logistics, commuting, energy demand, and resilience to shocks. Urban resilience research conceptualizes resilience not as a single outcome but as capacities to absorb, adapt, and transform under disturbances, emphasizing governance, social systems, and infrastructure interdependencies (Meerow et al., 2016). In the digital-green context, resilience extends to the robustness of data infrastructures and to the vulnerability of energy-intensive digital systems to climate risks (heat, water constraints for cooling, extreme events).

The required study by Gu and Kharytonova (2025) analyzes how the built environment and economic context jointly affect enterprise operations and proposes adaptive strategies (Gu & Kharytonova, 2025c). This perspective complements firm-level digital transformation research by adding spatial and infrastructural mediators: the same digital technology can yield different productivity and sustainability outcomes depending on whether firms operate in regions with reliable power, efficient logistics, and supportive industrial policy. The enterprise strategy literature on digital transformation similarly warns about “dark side” effects and the need for governance and capability complements, suggesting that built-environment constraints can magnify risks such as cybersecurity vulnerability, operational fragility, and energy cost exposure (Wang et al., 2023; IEA, 2025a).

A central macro constraint is the energy footprint of digital systems. The IEA estimates that data centers consumed about 415 TWh, or roughly 1.5% of global electricity consumption in 2024, with rapid growth since 2017; projected demand increases imply significant generation and grid implications (IEA, 2025a). Empirical literature also finds that digitalization can increase energy consumption overall due to direct ICT energy use and rebound effects, even if it improves efficiency in specific processes (Lange et al., 2020). Peng and Qin (2024) provide evidence that digitalization can trigger a rebound effect in electricity use, reinforcing the concern that efficiency gains may be offset by increased consumption (Peng & Qin, 2024). These findings imply that firm-level adaptation strategies must be energy-aware: compute efficiency, carbon-aware workload management, electrification planning, and procurement of clean power become integral to competitive strategy under carbon constraints.

Sector-Specific Applications: the Case of Digital Tourism

Tourism illustrates both the promise and limits of digital substitution. Tourism has a substantial carbon footprint, with major emissions driven by transport and consumption; global evidence indicates that demand growth has historically outpaced efficiency improvements, making mitigation a governance and demand-management challenge (Lenzen et al., 2018; Gössling et al., 2023). Digital tools in tourism can support sustainability through demand management (dynamic pricing, congestion control), smarter mobility, and partial substitution via virtual experiences.

The required article by Gu, Wang, Wang, and Wang (2025) develops a mechanism and practical path for digital tourism economy under environmental constraints (Gu et al., 2025f). This aligns with a broader literature on virtual reality (VR) tourism and digital experiences as a means to reduce physical travel demand or shift consumption toward lower-carbon activities. Talwar et al. (2022) argue that VR tourism can satisfy experiential demand without physical travel, presenting it as an unconventional sustainability-promoting innovation; however, net emissions effects depend on whether VR substitutes for high-carbon travel or merely complements it (Talwar et al., 2022). Gössling et al. (2023) emphasize that decarbonizing tourism requires multi-scale strategies, including policy constraints and corporate carbon management, implying that digital tools are best understood as portfolio instruments rather than standalone solutions.

This sector also highlights rebound and equity issues. If digital tools reduce costs or increase convenience, they may stimulate additional consumption (more trips, more digital entertainment energy use), and if digital tourism concentrates benefits among large platforms, local SMEs may be marginalized. Therefore, digital tourism provides a microcosm of the broader thesis: synergy requires governance, measurement, and distributional policy complements.

Synthesis and Critical Evaluation

Mechanism Synthesis: Enabling Pathways and Conditionalities

Across domains, the literature supports three core enabling pathways by which digital innovation can contribute to a green economy. First, measurement expansion: digital tools improve monitoring, traceability, and MRV, enabling better enforcement of environmental standards, more accurate carbon accounting, and more credible sustainable finance signals (Lagasio, 2024; Gorovaia & Makrominas, 2025). Second, optimization and efficiency: analytics and automation can reduce energy and material waste at process levels and improve logistics and grid management, potentially lowering emissions intensity (Wang et al., 2023). Third, innovation acceleration: digital transformation can promote green innovation through better information environments, reduced rent-seeking, and improved governance and disclosure, as firm-level evidence shows for green patent outcomes (Li et al., 2024).

However, each pathway is conditional. Measurement expansion yields real impact only under enforceable standards and auditability; otherwise it may increase strategic disclosure and greenwashing. Optimization yields net emission reductions only when rebound effects are managed and electricity is increasingly decarbonized. Innovation acceleration becomes socially sustainable only if skills systems and labor-market institutions distribute gains and enable worker mobility (OECD, 2023a; OECD, 2023b). This conditionality structure supports a "complements" model of synergy: digital technologies are enabling inputs whose net effect depends on governance, energy systems, and human capital.

Risks and "Dark Side" Dynamics

The review identifies three risk clusters that recur across the literature.

1) Algorithmic bias and inequality. AI can intensify inequality through wage polarization and rents; workplace algorithmic management can worsen job quality without governance, and adoption benefits can concentrate among capital owners and platform leaders (Acemoglu & Restrepo, 2022; OECD, 2023a; Rockall et al., 2025). Gu and Wang (2025) emphasize inequality as a central outcome of AI diffusion, aligning with this risk cluster (Gu & Wang, 2025a).
2) Environmental ethics and governance failures in green finance. ESG rating divergence is large and structurally driven, implying persistent uncertainty and scope for strategic behavior (Berg et al., 2022). Greenwashing detection research shows that NLP can identify disclosure anomalies, but also highlights risks of false confidence if models are trained on inconsistent labels or if enforcement is weak (Lagasio, 2024; Gorovaia & Makrominas, 2025). Gu et al. (2025e) contribute a normative lens emphasizing fairness and intergenerational equity in computational green finance (Gu et al., 2025e).
3) Energy footprint and rebound effects. Data center and AI electricity demand is material and rapidly growing; digitalization can increase total energy demand due to direct ICT energy use and rebound effects, complicating net-zero pathways (IEA, 2025a; Lange et al., 2020; Peng & Qin, 2024). This risk cluster is decisive for post-AI synergy because it transforms digital growth into a system constraint for decarbonization and for hydrogen electrification pathways (IEA, 2024; IEA, 2025a).

Research Gaps: Toward Non-Linear Coupling and Integrated Evaluation

Three gaps limit robust policy inference.

First, the literature lacks long-horizon causal evidence on non-linear coupling between digital transformation intensity and green outcomes. Emerging studies suggest threshold and diminishing-return patterns in green finance effects and digitalization impacts, but multi-decade causal identification remains rare (Liu et al., 2025). Second, joint modeling of environmental performance and distributional outcomes is insufficient: many studies examine emissions or productivity, fewer evaluate wages, rents, and employment simultaneously under AI diffusion. Third, integrated evaluation of AI-enabled green finance under heterogeneous disclosure regimes is limited, particularly regarding how standards (taxonomies, reporting mandates) interact with machine-learning-based assessment and with corporate strategic behavior (Berg et al., 2022; Nipper et al., 2025).

Future Research Directions and Conclusion

Future research should prioritize three agendas.

1) AI governance integrated with labor-market institutions. Empirical designs should link workplace AI adoption to task redesign, wage dynamics, and training interventions, explicitly testing whether policy can neutralize polarization while preserving productivity benefits (Acemoglu & Restrepo, 2022; OECD, 2023a).
2) Sustainable finance governance that combines standards, auditability, and AI-assisted supervision. Research should evaluate model performance and incentives under real enforcement settings, including false-positive/false-negative tradeoffs in greenwashing detection and the interaction between rating divergence and regulatory taxonomies (Berg et al., 2022; Lagasio, 2024; Nipper et al., 2025).
3) System-level evaluation of hydrogen and digital loads under constrained clean electricity. Work is needed on life-cycle carbon accounting, certification interoperability, and logistics bottlenecks for hydro-

gen, while explicitly modeling opportunity costs of clean power under rising AI electricity demand (IEA, 2024; IEA, 2025a; Gu et al., 2025d).

In conclusion, the literature supports a conditional-synergy thesis: digital innovation can accelerate green transition through measurement, optimization, and innovation pathways, but net benefits require complements—credible governance, equitable skill formation, and decarbonized energy supply. The post-AI era therefore shifts the core analytical question from technological feasibility to institutional feasibility: which governance architectures, capability policies, and infrastructure investments convert digital acceleration into an inclusive and durable green economy.

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