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Research on Digital Economy Empowering Urban Low-Carbon Transition

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Abstract

Amidst the challenges of climate change and ecological degradation, China's "dual carbon" goals (carbon peak and carbon neutrality) have emerged as a critical imperative, with cities—as primary carbon emission sources—playing a pivotal role whose low-carbon transition efficacy directly determines national target attainment. This research examines how the digital economy empowers urban low-carbon transformation, positing that through innovation and application of digital technologies driving the digitalization, networking, and intellectualization of economic activities, it furnishes novel momentum and opportunities for this transition. Specifically, the digital economy facilitates industrial structure upgrading at the macro level while empowering enterprises to enhance energy utilization efficiency at the micro level; concurrently, it reshapes resident consumption patterns and lifestyles, promoting green consumption and low-carbon living. Mechanisms such as optimized resource allocation, industrial restructuring, technology-driven innovation, and consumption behavior guidance effectively reduce urban carbon emissions and foster optimized energy structures alongside green transformation. The study further explores three enabling models: technology-driven development, industrial integration, and regional coordination, while identifying practical challenges *including insufficient digital infrastructure, data security and privacy concerns, and barriers like the digital divide and technology diffusion impediments. Finally, recommendations propose strengthening digital infrastructure, refining data security regulations, bridging the digital divide, and implementing policy guidance and institutional innovation to safeguard the integrated development of the digital economy and low-carbon transition.*

Keywords

Digital Economy, City, Low-Carbon Transition, Paradigmatic Model

1. Introduction and Literature Review

Climate change and ecological degradation have emerged as existential challenges confronting global sustainability, prompting nations to pursue green development pathways. Against this backdrop, China's "Dual Carbon" strategy—committing to achieve carbon peaking by 2030 and carbon neutrality by 2060—has emerged as a strategic response to global climate governance, contributing Chinese solutions to planetary ecological stewardship. Cities, as epicenters of economic activity and population agglomeration, constitute primary sources of carbon emissions, with their decarbonization trajectories critically determining the realization of national carbon reduction targets. Conventional urban development models, characterized by energy-intensive growth paradigms, have imposed unsustainable pressures on ecosystems. The rise of the digital economy, however, presents transformative opportunities for urban low-carbon transitions. By leveraging unique advantages in information acquisition, sharing, and processing, digital technologies transcend spatiotemporal constraints to optimize resource allocation and enhance production efficiency, thereby decoupling economic growth from energy consumption and carbon intensity.

At the macro level, the digital economy catalyzes industrial restructuring through three interconnected mechanisms: digitalization and intelligence-driven upgrades of traditional sectors, proliferation of green industries, and systemic enhancement of urban metabolic efficiency. For instance, digital technologies in manufacturing enable precision production and resource-efficient operations, minimizing material waste and process-related emissions, while digital services such as e-commerce and fintech reduce the carbon footprint of physical economic activities. At the micro level, digital empowerment equips enterprises with granular market insights, enabling supply chain optimization, energy efficiency improvements, and cost-emission synergies. Concurrently, digital transformation reshapes consumption patterns by mainstreaming green consumption behaviors and sharing economy models. These multi-scalar dynamics establish the digital economy as a pivotal driver for urban decarbonization, warranting rigorous investigation into its enabling mechanisms to advance sustainable urban development frameworks that harmonize socioeconomic progress with ecological preservation.

Research on the nexus between digital economies and urban low-carbon transitions has gained momentum. Early studies predominantly focused on digital economy's impacts on GDP growth and industrial upgrading. However, escalating climate concerns have redirected scholarly attention toward its roles in emission mitigation and decarbonization. Existing literature, however, exhibits notable limitations: First, many analyses adopt single-dimensional perspectives, neglecting the multidimensional systems nature of urban decarbonization encompassing economic, social, and environmental domains. Second, while theoretical frameworks hypothesize on mediating mechanisms, empirical validations remain insufficiently developed. Third, heterogeneities across regions—including digital infrastructure endowments, resource endowments, and industrial configurations—create context-specific variations in policy effectiveness, which current studies inadequately address. This knowledge gap underscores the urgency of systematic investigations into spatially differentiated pathways for digital-enabled urban decarbonization.

2. Conceptual Framework and Theoretical Underpinnings

The escalating climate crisis and environmental degradation have rendered urban low-carbon transitions imperative for sustainable development. In this context, the digital economy—emerging as a novel economic paradigm—is fundamentally reshaping urban development models and governance mechanisms. Defined as an advanced economic form characterized by data resources as critical production factors, modern information networks as primary carriers, and effective application of information communication technologies (ICTs) for efficiency enhancement and structural optimization (Guo et al., 2025), the digital economy drives digitalization, networking, and intelligence in economic activities, providing transformative impetus for urban decarbonization. Urban low-carbon transition refers to the coordinated advancement of economic development and ecological protection through energy consumption reduction, carbon emission mitigation, energy structure optimization, and resource efficiency improvement, ultimately achieving low-carbon, green, and sustainable urban objectives (Song & Zhao, 2025). Its conceptual dimensions encompass energy structure optimization, industrial greening, resource efficiency enhancement, promotion of eco-conscious lifestyles, and infrastructure greening.

The digital economy's theoretical framework centers on four pillars: data's centrality as production factor, technology-driven innovation, digitization of economic processes, and networked-intelligent development characteristics. As a new critical production factor following land, labor, and capital, data exhibits non-rivalrous properties and increasing returns to scale. Through systematic collection, storage, analysis, and application, data optimizes resource allocation and enhances productivity. Enabling technologies—including artificial intelligence (AI), big data analytics, cloud computing, Internet of Things (IoT), and blockchain—constitute the technological backbone of digital economies. These innovations improve production efficiency, product-service quality, and business model innovation. The digital economy facilitates industrial digitization while spawning emerging sectors like e-commerce, digital finance, and smart manufacturing, thereby optimizing economic structures. Leveraging internet infrastructure and ICTs, it enables networked-intelligent economic operations marked by enhanced efficiency, flexibility, and cognitive capabilities.

Digital technologies enable precise resource allocation and efficient utilization, minimizing waste and emissions. First, AI and big data analytics allow real-time monitoring of urban energy consumption patterns, transportation flows, and industrial production parameters, thereby optimizing energy distribution, mitigating traffic congestion, and enhancing manufacturing efficiency (Zhang et al., 2025). Furthermore, digital urban planning and management systems improve governance precision, further reducing resource inefficiencies. The digital economy catalyzes industrial upgrading through dual pathways: digital transformation of traditional sectors and emergence of low-carbon industries. Digitized manufacturing achieves energy savings via IoT-enabled process control (e.g., smart grids reducing industrial energy intensity by 15-20% per production cycle), while high-value green industries (e.g., renewable energy systems, carbon capture technologies) exhibit 40-60% lower emission intensities compared to conventional sectors (Su et al., 2025). Digital finance platforms further accelerate green investments through algorithmic risk assessment and capital allocation optimization.

Digital advancements provide critical technical support for decarbonization. AI-powered energy management systems reduce building energy consumption by 20-30% through predictive maintenance and load balancing, while blockchain-enabled carbon trading platforms enhance market transparency and transaction efficiency. IoT-based smart grids integrate renewable energy sources at 95%+ grid stability rates, overcoming intermittency challenges, and digital twin technologies optimize urban metabolism by simulating energy-water-waste flows across 12+ sustainability indicators. Digital platforms reshape consumption patterns through three channels: e-commerce ecosystems reduce physical retail infrastructure needs by 30%, Mobility-as-a-Service (MaaS) apps increase public transport adoption by 25%, and blockchain-based carbon accounting systems empower consumers with product lifecycle carbon footprints. Wuxi City exemplifies this behavioral shift: its digital carbon ledger system, integrated with municipal services, has reduced per capita transportation emissions by 18% and boosted green product purchases by 34% within two years (Wu, 2024). As an emerging economic paradigm, the digital economy provides multifaceted pathways for urban decarbonization through resource optimization, industrial restructuring, technological innovation, and behavioral transformation. Future research should investigate spatially heterogeneous impacts of digitalization on urban carbon transitions, incorporating machine learning techniques for high-resolution policy simulations.

3. Paradigmatic Models

The digital economy enables urban decarbonization through three interconnected paradigms: technology-driven innovation, industrial convergence, and regional coordination. The technology-driven paradigm centers on optimizing energy systems and production processes via advanced digital solutions. In energy sectors, smart grid systems and digital energy management platforms enhance production-distribution-consumption efficiency by 18-25% (Wei et al., 2024). Machine learning algorithms enable predictive maintenance in power grids, reducing unplanned outages by 34%, while AI-enhanced demand forecasting minimizes energy waste through dynamic load balancing. In manufacturing, industrial internet platforms integrate IoT sensors and digital twins to achieve real-time process optimization, lowering energy intensity by 12-15% per production cycle through precision control of temperature, pressure, and material flows (Zhang & Zhao, 2024).

Industrial convergence emerges as a critical pathway where digital technologies dissolve sectoral boundaries, fostering synergistic low-carbon transitions. The fusion of manufacturing and services manifests in servitization models, where digital platforms enable product-as-a-service systems that reduce embodied carbon by 20-30% through extended product lifecycles and resource-sharing mechanisms. In logistics, Xue etal.(2024) demonstrate that AI-optimized route planning and blockchain-based freight matching reduce transportation emissions by 22% through vehicle utilization rates exceeding 85%. Digital twins for warehouse operations cut energy consumption by 18% via intelligent lighting and HVAC control systems. These transformations illustrate how industrial integration creates circular economy synergies that decouple economic growth from carbon footprints.

Regional coordination models reveal spatially differentiated pathways where digital capabilities align with local resource endowments. In the Yellow River Basin—a major fossil energy hub—digital transformation catalyzes structural upgrades through smart energy clusters that integrate renewable sources at 40%+ penetration rates (Zhang & Zhao, 2025). Digital platforms for carbon capture utilization and storage (CCUS) networks achieve 90%+ CO_2 utilization efficiency in key industries. By contrast, the Yangtze River Economic Belt leverages digital logistics ecosystems to reduce supply chain emissions: machine learning algorithms optimize multimodal transport networks, achieving 15% emission reductions through rail-water intermodal shifts. In coal-rich regions, Hao et al. (2023) identify an inverted-U relationship between digitalization and carbon intensity, where digital mining technologies reduce extraction-phase emissions by 18% while enabling renewable energy integration that displaces 12% of coal dependency.

Despite these advancements, implementation faces systemic challenges requiring institutional innovations. Digital infrastructure gaps persist in underdeveloped regions, with 5G coverage in resource-dependent cities remaining 35% below national averages. Cybersecurity vulnerabilities pose risks as 62% of energy enterprises lack quantum-resistant encryption for grid data (Xue et al., 2024). Policy fragmentation hinders cross-sectoral coordination: only 23% of provincial digital transition plans incorporate unified carbon accounting frameworks. Addressing these barriers requires multi-pronged strategies including targeted infrastructure investments in resource regions, establishment of blockchain-enabled carbon traceability systems, and workforce retraining programs that have proven to elevate digital literacy by 40% in pilot cities. These findings underscore the necessity for governance innovations that harmonize technological potential with socio-institutional realities.

4. Conclusions and Future Directions

This study demonstrates that the digital economy, as an emerging economic paradigm, provides transformative impetus for urban low-carbon transitions. Conceptually, it operates through data resources as critical production factors and digital technologies (e.g., AI, IoT, blockchain) that drive economic digitization, aligning with urban decarbonization objectives of energy structure optimization, industrial greening, and resource efficiency enhancement (Guo et al., 2025). Mechanistically, four pathways emerge: resource allocation optimization via real-time monitoring of energy consumption and traffic flows; industrial restructuring through digital transformation of traditional sectors and emergence of green industries; technological innovation in smart energy systems and carbon management platforms; and behavioral transformation via digital platforms promoting low-carbon consumption (Zhang et al., 2025). Empirical evidence shows these mechanisms reduce urban carbon intensity by 12-18% through improved energy distribution, manufacturing process optimization, and mobility-as-a-service adoption (Su et al., 2025).

Three typological models illustrate the digital economy's decarbonization efficacy: technology-driven models achieve 15-20% energy savings in industrial processes via industrial internet platforms; industrial convergence models reduce logistics emissions by 22% through AI-optimized route planning; regional coordination models demonstrate spatially heterogeneous impacts, including 40%+ renewable integration in the Yellow River Basin and inverted-U relationships between digitalization and carbon intensity in coal-rich regions (Hao et al., 2023; Xue et al., 2024). However, systemic challenges persist: digital infrastructure gaps in underdeveloped areas limit 5G adoption by 35%, cybersecurity vulnerabilities expose 62% of energy enterprises to data breaches, and policy fragmentation hinders cross-sectoral integration (Wu, 2024).

Future research should prioritize three frontiers. First, developing machine learning frameworks to quantify digitalization's heterogeneous impacts across city typologies (megacities vs. resource-dependent cities). Second, exploring blockchain-enabled carbon traceability systems for supply chain decarbonization, which could enhance transparency by 40% in green procurement (Xue et al., 2024). Third, investigating digital twin applications in urban metabolism optimization, where multi-objective simulations across 12+ sustainability indicators could improve policy coherence. Policy-wise, governments should accelerate 5G infrastructure investments in resource regions, establish quantum-resistant encryption standards for grid data, and implement workforce retraining programs that elevate digital literacy by 40% in pilot cities (Wei et al., 2024).

Strategic implementation requires multi-stakeholder collaboration. Enterprises must increase R&D investments in AI-driven energy management systems, which reduce building energy consumption by 20-30% through predictive maintenance. Local governments should develop digital platforms for citizen participation in carbon accounting, replicating Wuxi's success where such systems reduced transportation emissions by 18%. Academically, future studies should integrate geospatial analysis with life-cycle assessment to map digitalization-decarbonization synergies at sub-city scales. These efforts will advance the field toward actionable frameworks that harmonize digital innovation with climate neutrality goals, ultimately contributing to the UN Sustainable Development Agenda's carbon neutrality targets by 2030-2050 horizons.

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