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Digitalization, Green Innovation, and Green Transformation of Energy Enterprises in China

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Abstract

This paper utilizes panel data from Chinese A-share listed energy companies on the Shanghai and Shenzhen stock exchanges from 2007 to 2022, employing methods such as the three-step method and bootstrap decomposition to explore the relationship between digitalization and the transformation of energy companies. It further analyzes the underlying mechanisms through the intermediary variable of green innovation. Additionally, the paper investigates the moderating effects of environmental regulations and corporate carbon intensity on digitalization. The findings reveal that digitalization has a significant positive effect on the green transformation of energy companies, and green innovation plays a partial mediating role in promoting green transformation through digitalization. This promotional effect remains valid even after green innovation is divided into two dimensions: green R&D efficiency and green technology transfer levels. Furthermore, increased carbon intensity enhances the role of digitalization in promoting the green transformation of energy enterprises, while environmental regulations diminish this effect. At the same time, when environmental regulations and carbon intensity both interact synergistically with digitalization in green innovation, their combined impact on green innovation is negative. Heterogeneity analysis indicates that the mediating effect is significantly higher for Chinese energy companies in central and western regions, particularly those in non-state-owned, large-scale, and low-pollution sectors, compared to those that are in eastern regions, state-owned, small and medium-sized, and in high-pollution sectors. The research conclusions have significant implications for promoting the digital transformation of energy companies, enhancing their green innovation capabilities, and advancing the green transformation of the energy sector.

Keywords: digitalization; green innovation; green transformation

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1. Introduction

The ecological pattern of contemporary Earth is undergoing profound evolution. 2023 became the hottest year on record, with the global average temperature increasing by about 1.2 °C. The atmospheric carbon dioxide concentration exceeded 420 ppm, which was 50% higher than before the Industrial Revolution. Frequent extreme weather events confirm the climate model prediction: in 2023, wildfires in Canada were expected to release 300 million tons of carbon, the peak of the heat wave in Europe exceeded 48 °C, and floods in Pakistan covered one-third of the country. In the process of coping with this ecological change, the European Union's Digital Decade (2030) and the United Nations Sustainable Development Goals (SDGs), among other policies, provide institutional support. Moreover, China's "14th Five-Year Plan" and the outline of long-term goals by 2035 clearly set out the phased tasks of peak carbon dioxide emissions and achieving carbon neutrality. The green transformation of enterprises not only reflects the responsibility of enterprises for the environment but is also the only way for their strategic transformation. With the promotion of environmental standards and the growing trend of green consumption, green innovation has become a key component of enterprises' sustainable development strategies. Green innovation not only helps enterprises reduce environmental pollution and improve energy efficiency, but also enhances their brand value and market competitiveness, attracting more investment and cooperation opportunities. Green innovation and green transformation have significant practical implications for shaping the future of enterprises, promoting sustainable development, and enhancing the economic and environmental impacts of enterprise activities [1].

Against the backdrop of the accelerated evolution of global climate governance and the in-depth development of the energy revolution, the energy industry is facing unprecedented transformation pressure. According to the International Energy Agency (IEA), the global energy industry accounts for 73% of carbon emissions, and achieving a green transformation in this sector has become a key breakthrough in addressing climate change. In 2023, the meeting of the China Central Committee for Deep Reform further emphasized "deepening the reform of the energy system and mechanism and promoting clean, low-carbon, and efficient use of energy," which pointed out the development direction of "digital empowerment and green leading" for the energy industry. Green innovation and green transformation are the new engines driving the high-quality development of the energy industry and the entire economic system. The rapid development of digital technology also presents new opportunities and challenges for energy enterprises to achieve a green transformation.

Relevant research indicates that digitalization drives the green transformation of energy enterprises through multiple mechanisms. It acts upon this transformation via three direct pathways: technological empowerment (enhancing efficiency), information transparency (optimizing governance), and market connectivity (creating value). For instance, digital technologies such as artificial intelligence, the Internet of Things, and blockchain significantly reduce energy consumption and carbon emissions by optimizing resource efficiency and process monitoring [2,3]. Here, artificial intelligence primarily functions as a hub for intelligent decision-making, processing vast datasets to optimize energy system operations. Internet of Things technology, through the deployment of extensive sensor networks, enables comprehensive perception and real-time interconnection across all stages of energy production, transmission, and consumption. Blockchain technology, with its decentralized, immutable, and traceable characteristics, establishes a trustworthy environment for transactions and governance in the green energy transition. Concurrently, digital platforms facilitate "digital-green value co-creation" by integrating fragmented resources and innovating business models, thereby propelling the development of circular economies (Ma and Lin, 2023 [4]; Luo et al., 2023 [5]).

Moreover, green innovation serves as the core engine for energy enterprises to achieve green transformation, with its mechanism primarily manifested in three aspects: technological innovation, business model restructuring, and policy coordination. At the technological level, green process innovation and green product innovation significantly reduce carbon emission intensity by optimizing production processes and end-use energy efficiency (Chen et al., 2006 [6]). At the business model level, green innovation drives enterprises to shift from focusing solely on economic value towards pursuing the integration of economic, environmental, and social value. This compels companies to fundamentally rethink their operational approaches, thereby catalyzing systemic innovation in business models. Consequently, environmental externalities are 'internalized' as new competitive advantages, facilitating the green transformation of energy enterprises. Yang Fang et al. [7] argue that digitalization constructs green production development models by enhancing green technological innovation, optimizing resource allocation, and reducing knowledge search costs [8], thereby elevating new-quality productive forces and providing crucial support for enterprises to achieve sustainable development within complex and volatile economic environments [9]. Corporate green innovation serves as a vital pathway for enterprise transformation and upgrading. By reducing energy intensity and producing green products, green innovation generates dual economic and environmental value effects, proving crucial for the sustainable development of manufacturing. Green innovation also serves as a key means for enterprises to address environmental uncertainties and stakeholder environmental concerns, helping to reduce the environmental burden of production activities and enhance resource utilization efficiency [10].

Additionally, research indicates that environmental regulations and carbon performance play a moderating role in the relationship between digitalization and green transition. First, the moderating effect of environmental regulations is not simply "the stronger, the better." For instance, a U-shaped relationship may exist between environmental regulations and digital transformation, implying that policymakers must carefully calibrate the intensity of regulations. Excessively stringent regulations in the early stages may suppress corporate investment, whereas long-term, stable, high-intensity regulations are more effective in stimulating innovation. Second, synergies between digital technologies and green finance can significantly enhance regional carbon emission performance, with this effect being more pronounced in areas with weaker environmental regulations. This indicates that carbon performance targets themselves can modulate the synergistic effects between digital and green initiatives [11].

China is globally recognized as an energy superpower, having established the world's most comprehensive and largest energy system. The green transition of energy enterprises is crucial for achieving the dual carbon goals and safeguarding energy security. The effectiveness of this transformation directly impacts China's progress towards carbon peaking and carbon neutrality, serving both to reduce its own high carbon intensity and to act as a driving force for green economic and social development. Compared to manufacturing, China's energy enterprises possess unique characteristics stemming from three overlapping attributes: Firstly, they account for 73% of global carbon emissions, exhibit high intensity, and are directly regulated by dual-carbon policies, making carbon reduction an imperative requirement. In contrast, manufacturing focuses primarily on compliance, with carbon reduction being an optional consideration. Secondly, core assets such as power plants involve substantial investment and prolonged operational lifespans. Digital transformation must adapt to ageing infrastructure, entailing high costs and slow returns, whereas manufacturing digitalization offers greater flexibility. Finally, energy enterprises function both as producers and high-energy consumers, necessitating a dual-track transformation: reducing their own emissions while helping other sectors reduce their carbon footprint. Manufacturing, by contrast, focuses solely on emissions control at the production end. Regarding traditional energy transition and new energy development, conventional energy sources are enhancing supply security and reducing carbon through clean, efficient technological upgrades. Meanwhile, China leads globally in new energy, ranking first across the industrial chain, energy storage, and new energy vehicles in the first quarter, establishing it as the core driver of energy transformation. As resource-based enterprises, energy companies can not only provide more efficient and environmentally friendly green energy to reshape the energy supply–demand landscape, but also compel traditional energy firms to enhance energy conservation, emission reduction, and carbon mitigation. This facilitates the green transformation of energy enterprises themselves, promotes optimized energy utilization, and ultimately advances sustainable development goals [12].

Existing research has focused on digitalization and the green transition of manufacturing enterprises. Further exploration is required to understand how digitalization influences the green transition of energy enterprises, their underlying mechanisms, and the factors that affect this relationship. This paper employs fixed-effects models and Bootstrap decomposition methods to empirically analyse the impact of digitalization on the green transition of energy enterprises, utilizing panel data from energy companies listed on the Shanghai and Shenzhen A-share markets between 2007 and 2022. Building upon existing research, this study makes several key contributions: Firstly, the study extends beyond the manufacturing sector examined in existing literature to focus on the energy industry, which is more intrinsically linked to green transition development. Secondly, while maintaining the emphasis on green innovation as a mediating factor in digitalization's promotion of corporate green transition, this study moves beyond the single metrics commonly used in existing literature (such as green patent applications or green patent grants). Instead, it employs two more comprehensive and systematic indicators—green R&D efficiency and green technology transfer efficiency—to elucidate the operational mechanisms of green innovation. Subsequently, the paper examines the moderating effects of environmental regulations and carbon intensity on the promotion of green transformation by digitalization within energy enterprises. It further analyzes the joint impact of environmental regulations and carbon intensity, each in synergy with digitalization, on green innovation. Notably, among the moderating variables, carbon intensity was selected specifically for its relevance to the characteristics of energy enterprises. Finally, the study examines the heterogeneous effects of the digital economy on enterprises differing in geographical location, ownership structure, scale, and energy type. This enriches research on the digital economy and green transformation, providing more comprehensive economic theoretical analysis and policy support for the sustainable development of energy enterprises.

2. Literature Review and Research Hypotheses

This research is based on a literature review combined with the experience and facts of accelerating digital transformation of energy enterprises under the background of rapid development of digital economy. Data were sourced from the State Council's "14th Five-Year Plan for Digital Economy Development 2022". By systematically combing the cross-research literature of digital transformation and green transformation, this paper constructs a theoretical framework of "digitalization → green innovation → green transformation" to reveal the dual mechanism of digitalization affecting the green transformation of energy enterprises (such as Figure 1).

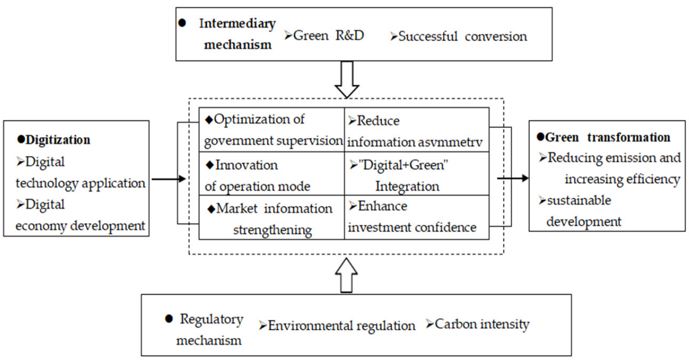

Figure 1. Theoretical analysis framework.

2.1. The Direct Impact Mechanism of Digitalization on the Green Transformation of Enterprises

With the rapid advancement of the digital economy, digital transformation has become a driving force for enterprises to achieve high-quality economic development. China's digital economy has developed at a swift pace, effectively propelling the nation's social development towards a stage of high-quality growth, with initial successes in green transition [13]. Within the green transition of energy enterprises, digitalization likewise plays a crucial role. Emerging technologies have emerged and matured, fostering digital infrastructure and application technologies that have unleashed new vitality at the corporate level.

Some literature has explored the mechanisms through which digitalization influences green transformation. Different studies have focused on varying aspects of digitalization's direct effects. Ran, Yang, Yan, Xu, & Cao (2023) [14] and Sun et al. (2022) [15] place greater emphasis on the pivotal role of digitalization in mitigating information asymmetry. Digitalization is regarded as crucial for effectively reducing information asymmetry between the government and enterprises while facilitating corporate green transformation. For governments, digitalization enables the collection of environmental data throughout the traceable process of corporate value creation, overcoming information barriers faced by corporate leadership. This provides a targeted, dynamic foundation for policy formulation, subsidy issuance, supervision, and inspection. For enterprises, digitalization allows governments to enhance regulatory standards and transparency in resource allocation, thereby curbing speculative behavior and bolstering confidence and certainty among green-transitioning firms. Simultaneously, according to signalling theory, green development actions presented through digitalization can send positive signals to market participants, bolstering investment confidence in social capital and guiding the aggregation of production factors, which in turn promotes green transition. Some scholars, adopting an operational management perspective, emphasize that digitalization directly enhances production efficiency (Pan et al., 2022 [16]). In summary, it can be concluded that digitalization exerts a significant positive influence on the green transition of manufacturing companies.

Several studies have confirmed that digitalization can assist manufacturing enterprises in achieving a leap in green transformation, subsequently forming a new model of integrated development known as "Digital + Green" (He et al., 2022 [17]; Meng et al., 2022 [18]), enabling harmonious integration of environmental protection, business development, and social responsibility. From a sales and service perspective, digitalization introduces new transformations to manufacturing enterprises' marketing models, business models, and service models, while promoting corporate green transformation by facilitating green development on the demand side. Digitalization in services enables enterprises to provide targeted consultancy and services to clients, fostering intelligence, proactivity, and personalization. This enhances the enterprise's green image and further accelerates green transformation.

Digitalization also holds significant potential to drive the green transformation of industrial enterprises (Meng and Zhao, 2022 [19]). Particularly under the dual imperatives of global warming and carbon neutrality targets, industrial green transformation has become an inevitable choice [20]. Digital technologies can facilitate digital transformation within traditional industrial sectors, thereby establishing production models that are both environmentally friendly and energy-efficient, aligning with the essence of green transformation. The integration of digital technologies, such as 5G, with industry promotes a shift towards informatization, intelligentization, and clean production. This holds significant importance for accelerating industrial green transformation and establishing a new development paradigm that balances ecological and economic benefits (Wang et al., 2023 [21]). The digital economy has spawned new production factors, models, organisational forms, industries, and business formats, such as smart manufacturing, platform economies, and the industrial internet. This has not only fuelled a surge in digital technologies but also transformed traditional production concepts and models within industrial enterprises, segmenting existing industrial paradigms and thereby propelling the green transformation of industrial firms (Du and Ren, 2023 [22]). The aforementioned mechanism of digitalization enabling corporate green transformation has been validated in manufacturing and industrial enterprises, and this fundamental logic chain remains applicable to energy enterprises. However, current micro-level research has primarily focused on the role of Industry 4.0 in enhancing supply chain management, green technologies, and the sustainability of environmental performance (Wen et al., 2021 [23]; Mastos et al., 2020 [24]). There remains a lack of exploration into the direct impact mechanisms of digitalization on green transformation. Therefore, this paper proposes Hypothesis 1:

H1: *Digitalization can significantly promote the green transformation of Chinese energy enterprises.*

2.2. The Indirect Impact Mechanism of Digitalization on the Green Transformation of Enterprises

2.2.1. Digitalization Drives Green Innovation

Digital technologies have become the core driver of green innovation within innovation ecosystem strategies. Consequently, investigating whether the digital economy can foster green technological innovation is crucial, as it helps reconcile economic growth with environmental protection more effectively. Current literature contains limited research on the direct link between the digital economy and green innovation. Most scholars explore aspects such as the digital economy and the green economy, the digital economy and innovation, and digital finance and green technological innovation. However, some literature, either indirectly or directly, reveals pathways and supporting evidence suggesting that digitalization may hinder green innovation. These can be summarised under two primary pathways: resource pressure and overconsumption. Firstly, the digitalization process itself entails substantial energy consumption and resource demands. The production, use, and disposal of digital technology-related products increase energy expenditure, potentially exacerbating environmental degradation. This creates a direct resource squeeze effect on green innovation. Secondly, by expanding information channels and market scale, the digital economy may exacerbate supply–demand fluctuations, inducing demand-driven overconsumption. This shifts corporate focus towards market responsiveness rather than long-term investment in green technology, thereby inhibiting profound green innovation.

However, most literature places greater emphasis on the promotional role of digitalization in green innovation. For instance, digital transformation can enhance information-sharing efficiency through the application of digital technologies [25], effectively mitigating information asymmetry [26], optimising resource allocation [27] and enhancing corporate governance [28], thereby exerting a positive influence on green innovation [29]. Notably, Wang et al. (2022) [30] emphasise that as a new economic form, the digital economy exerts a critical influence on green innovation. This aligns with the findings of Dai et al. (2022) [31]. Wei et al. (2022) [32] examined the relationship between the digital economy and green innovation, using Chinese cities as a basis, are found that the digital economy can effectively enhance urban green innovation output. Furthermore, within the context of the digital economy [33]. Enterprises leverage digital technologies to optimise R&D processes, employ digital organisational models to enhance R&D management, and strengthen the efficiency of information exchange and resource interaction in green innovation collaborations. This, in turn, drives the advancement of green technological innovation [34]. Moreover, the digital economy exhibits characteristics conducive to inclusive development in small and medium-sized cities, implying its potential to foster synergistic green innovation between large cities and smaller urban centres. However, existing research faces limitations in addressing endogeneity issues. Concurrently, studies highlighting the impact of differing developmental stages and regional disparities within the digital economy on green innovation offer valuable insights into the complex interplay between these phenomena.

Specifically, driven by digital technology, the interaction among digital enterprises, digital markets, digital users, and digital governments has formed a digital ecosystem where digital resource elements are interactively shared. This digital ecosystem breaks through the constraints of organizational boundaries and technological distances, providing numerous opportunities for enterprises to cross-border search for digital green knowledge. Digital technology can help overcome spatial and resource constraints, expanding the scope and process of green innovation. This will not only significantly enhance connectivity among green innovation participants but also facilitate the efficient utilization of digital green resources. Concurrently, manufacturing enterprises can utilize big data analytics to formulate optimisation plans for environmental challenges, alleviate pressure on natural resources, and foster green innovation [35]. Additionally, existing research indicates that digital technology can alleviate information asymmetry issues for enterprises and enhance information sharing levels, thereby driving the integration of R&D resources and knowledge [36], and promoting corporate green innovation. Additionally, by reducing agency costs, digital technologies free up capital and management resources, enabling their reallocation to productivity activities, including green innovation.

In addition to directly reducing the cost of resource utilization for businesses, digitalization also influences corporate green innovation by improving management efficiency [37]. As companies adopt digital tools for performance tracking and reporting, managerial incentives become more closely aligned with quantifiable long-term outcomes rather than opaque short-term financial metrics [38]. This shift in incentive structures can further encourage investment in innovation, particularly in areas such as green technology, where returns may take longer to materialize. Additionally, highly digitalized companies are better equipped to identify and leverage institutional pressures related to environmental sustainability. First, these companies have more digital tools to integrate green innovation into their business models. Like cloud computing, data-driven decision-making, and smart manufacturing technologies can enhance companies' ability to efficiently implement environmentally friendly processes. Second, digital companies are typically more flexible and can proactively respond to evolving environmental regulations and market expectations. Their adaptability enables them to meet stricter sustainability standards without sacrificing operational efficiency [39]. Consistent with the above research findings, this paper proposes Hypothesis 2:

H2: *Digitalization can significantly enhance the green innovation of Chinese energy enterprises.*

2.2.2. Green Innovation Drives Corporate Green Transformation

Recent public awareness of environmental issues has brought green innovation into the spotlight, highlighting its role in promoting environmental protection through eco-friendly products, improving operational and organizational efficiency, and enhancing business performance and competitive advantage [40]. Green transformation is a sustainable development model guided by sustainable development theory [41], led by the concepts of green growth and green development, and centered on green innovation, aiming to achieve energy conservation, emissions reduction, quality improvement, efficiency enhancement, environmental improvement, and a win–win situation for both environmental and economic benefits. Against the backdrop of the green transition, enterprises must develop dynamic capabilities that adapt to shifts in environmental regulations, market demands and technological advancements, thereby ensuring the sustainability, and effectiveness of green innovation [42]. Green innovation involves developing new ideas, products, and processes to minimize environmental impact. By leveraging green innovation, businesses can transform their environmentally conscious efforts into tangible competitive advantages. Cultivating an innovation culture that emphasizes sustainability enables companies to enhance productivity [43], minimize environmental impact, and gain a competitive advantage [44]. The green transformation of Chinese enterprises is a complex endeavor that involves various factors, including human resources, finance, technology, policy, and the environment. It must not only consider sustainable economic development but also environmental friendliness, aiming to achieve comprehensive sustainable green development in production [45], creating a win–win situation for economic growth and environmental protection [46].

Previous studies have confirmed that green technological innovation is conducive to increasing the added value of manufacturing, promoting the transformation of manufacturing from labor-intensive to technology-intensive, and guiding the development of energy-saving and emission-reduction technologies and low-carbon technologies [47]. Using environmental regulation as a moderating variable to examine the relationship between technological innovation [48], government behavior, and the green transformation of manufacturing. The findings indicate that green innovation has a positive impact on the green transformation of manufacturing. Green innovation also enhances firms' adaptability to environmental regulations and customer demands, promoting sustainable development and competitive advantage [49]. Miao et al. (2017) [50] explored the impact of green technological innovation on natural resource utilization efficiency through the application of Stochastic Frontier Analysis. Findings indicate that green innovation serves as a key driver for achieving green transformation and corporate sustainability. Additionally, green technological innovation, as an exogenous variable of economic growth, promotes economic development through the accumulation and enhancement of knowledge [51]. Existing research has also analyzed the relationship between green technological innovation and green economic development. Empirical tests reveal a significant positive correlation between the two [52].

Although the literature directly demonstrating 'inhibition' is less extensive than that proving 'promotion', several studies have highlighted this risk. This primarily manifests as the 'crowding-out effect' on innovation resources and transition costs. For instance, some empirical research has found that under stringent environmental regulations, innovation investments made by enterprises to meet compliance requirements may crowd out general R&D expenditure (Jaffe and Palmer, 1997 [53]). Moreover, for firms in traditional high-carbon industries, transitioning to green technologies entails substantial sunk costs and new investment expenditures. Particularly concerning "disruptive" green innovations, existing technological knowledge, organisational processes, and supply chain systems may become obsolete, creating a "capability trap". In such circumstances, enterprises (especially small and medium-sized enterprises) may opt for a wait-and-see approach or even resist change due to their inability to bear the high transition costs and organizational transformation pains, thereby delaying the green transformation process across the entire industry. Since most of these studies focus on digital outcomes when discussing green innovation, this paper proposes Hypotheses 3 and 4:

H3: *Green innovation promotes the green transformation of enterprises.*

H4: *Digitalization can promote the green transformation of Chinese energy enterprises through green innovation.*

2.3. The Regulatory Role of Environmental Regulations and Carbon Intensity

2.3.1. Environmental Regulation

Environmental regulations exert significant inhibitory effects on digital development, primarily manifesting in policy constraints and corporate transformation costs. During China's early stages of economic development, under weak environmental regulations, government performance evaluations prioritized economic growth over environmental protection. The digital industry was still in its infancy, and the application of digital technology in environmental governance was limited, resulting in suppressed penetration of digitalization across multiple sectors [54]. As environmental regulations intensify, enterprises must allocate significant resources to pollution control in order to meet compliance requirements, thereby diverting capital and technological investments away from digital transformation [55]. Especially in the heavy industry sector, stringent carbon emission control policies may force high-energy-consuming enterprises to prioritize environmental compliance issues rather than advancing digital upgrades [56,57].

It is worth noting that environmental regulations may also drive digitalization through promotional mechanisms, because during the high-quality development phase, stringent environmental regulations and digital industry development form a synergistic effect: the government promotes the adoption of technologies such as artificial intelligence and blockchain by enterprises to optimize production processes through the construction of a digital environmental governance system [58,59]. Research has found that when the intensity of environmental regulation crosses a specific inflection point, its promotional effect on digital technology becomes evident, such as through policy pressure compelling enterprises to utilize digital means to enhance resource utilization efficiency [60].

2.3.2. Carbon Intensity

The driving mechanism of carbon intensity for digitalization manifests primarily through two aspects: external pressures formed by policy regulations and market demands, and internal motivations driven by enterprises' pursuit of efficiency and compliance. On one hand, to address increasingly stringent carbon emission constraints, both central and local governments have simultaneously prioritized digitalization and decarbonization as policy focal points. This external environmental pressure compels enterprises to seek effective pathways for reducing emissions. High carbon intensity thus becomes a significant external driver for enterprises pursuing digital transformation. To reduce carbon emissions, meet regulatory requirements, and enhance operational legitimacy and stability, enterprises actively explore and adopt digital technologies to achieve precise monitoring and intelligent optimization of energy consumption and emission processes [61,62]. Additionally, low-carbon market demand and green investor preferences constitute market pressures, driving enterprises to leverage digitalization to build green competitiveness and brand image. Internally, reducing carbon intensity directly correlates with enhancing energy and resource efficiency, aligning closely with enterprises' intrinsic goals of cost reduction and efficiency improvement. Consequently, to achieve dual objectives of energy conservation, emissions reduction, and cost control, enterprises possess an intrinsic motivation to proactively invest in digital technologies. This enables the rationalization of production organization and optimal resource allocation through digitalization [63]. Therefore, this paper proposes Hypothesis 5:

H5: *The effect of digitalization level on the green transformation of energy enterprises will be influenced by environmental regulations and the carbon intensity level.*

3. Research and Design

3.1. Sample Selection and Data Source

This paper utilizes panel data from listed energy enterprises in Shanghai and Shenzhen A-shares from 2007 to 2022 for research purposes. The selected industries include electric power, thermal production and supply, ferrous metal mining and dressing, ferrous metal smelting and rolling processing, coal mining and washing, gas production and supply, oil and natural gas mining, petroleum processing, coking and nuclear fuel processing, nonferrous metal mining and dressing, and nonferrous metal smelting and rolling processing. The financial data of listed companies comes from the Wind data platform and the CSMAR data platform. And follow the following principles: eliminate enterprises such as ST and *ST, and eliminate enterprises in the financial industry. Through the above adjustments, 3380 valid sample data were finally obtained.

3.2. Variable Design

3.2.1. Explained Variables

Level of green transformation. Based on the research [64], this paper uses the text information disclosed in the annual report to measure the green transformation of enterprises. Select 113 keywords of green transformation of enterprises, including green development, circular development, low-carbon development, sustainable development, green building, etc. Then, count the frequency of each keyword in the annual report of listed enterprises, form the frequency of green transformation words, and use the frequency of the word plus 1 to take the natural logarithm to describe the green transformation of enterprises.

This text-based keyword frequency measurement method, while capable of quantifying green transformation through large-sample data, may introduce the following biases due to inherent textual characteristics: First, keywords may exhibit semantic ambiguity across different contexts—for instance, certain terms in annual reports may not directly indicate substantive green transformation actions, yet are included in the statistics. Second, companies may engage in “greenwashing” through text—artificially inflating environmental credentials by overusing green keywords in annual reports while failing to align actual green transformation actions with textual claims. Third, relying solely on annual report text data fails to comprehensively reflect green practices in daily operations and supply chain collaborations, potentially resulting in incomplete measurements of green transformation levels.

3.2.2. Explaining Variables

Degree of digital transformation (DIG). This paper adopts the research methodology proposed by Zhen Hongxian (2023) [65] and utilizes the Corporate Digital Transformation Index from the CSMAR China Listed Companies Digital Transformation Research Database as a proxy variable for measuring corporate digital transformation levels. A higher digital index indicates a higher level of digital transformation. This index is constructed based on multiple types of public information, including annual reports, fundraising announcements, and qualification certification announcements, to evaluate corporate digitalization levels. It primarily encompasses six major indicators: strategic leadership, technological drive, organizational empowerment, digital outcomes and applications at the listed company level, and environmental support at the macro level, thereby establishing an evaluation system for the corporate digital transformation index. Compared to existing literature (Yuan Chun et al., 2021 [66]) that focuses solely on Management Discussion and Analysis (MD&A) texts, this dataset enables more effective, comprehensive, and precise measurement of corporate digitalization levels. On one hand, the data covers 5226 enterprises and over 41,000 samples, with the full data range of the Digital Transformation Index spanning back to 2011, meeting the requirements for long-term panel studies. On the other hand, the index is synthesized through a "metric standardization + weighting" approach. Digital Transformation Index = 0.3472 × Strategic Drivers Score + 0.162 × Technological Enablement Score + 0.0969 × Organizational Enablement Score + 0.0342 × Environmental Enablement Score + 0.2713 × Digital Outcomes Score + 0.0884 × Digital Application Score). This approach eliminates dimensional differences while distinguishing the relative impact of each dimension on transformation through the use of weighted coefficients. Ultimately, the level of the digital index directly reflects the strength of an enterprise's transformation capabilities.

3.2.3. Mediating Variables

Green innovation level (INNO). Referring to Xiao Renqiao's practice, the green innovation efficiency of enterprises is divided into green science and technology research and development efficiency (STUDY) and green science and technology achievement transformation efficiency (CHANGE). In the stage of green technology research and development, the full-time equivalent of enterprise R&D personnel and internal expenditure of R&D funds are selected as initial inputs, and the number of enterprise patent applications, effective invention patents, and green invention patent applications are used as intermediate output indicators. In the transformation stage of green achievements, the intermediate output is the input in this stage, and the new product development funds and the introduction, digestion and absorption expenses are selected as the additional inputs in the transformation stage of achievements, and the sales income of new products, the output value of high-tech industries and the comprehensive environmental index are taken as the final output indicators [67].

3.2.4. Moderating Variables

Environmental regulation (Regulate1, Regulate2), carbon intensity (Intensify). The regulate1 method draws upon Chen et al. (2016) [68], measured by the proportion of words related to "environmental protection" in provincial government work reports relative to the total text volume. This approach reflects the intensity of government environmental governance while mitigating endogeneity issues. Following Fan Hongmin's (2017) [69] approach, the measure is calculated by the ratio of total industrial pollution control investment in the province where the enterprise is located to its industrial added value. Carbon intensity is defined as carbon emissions divided by operating revenue, following the methodology of Bolton and Kacperczyk (2021) [70].

3.2.5. Control Variables

In order to exclude the influence of other factors on the financial performance of enterprises, the following control variables are selected in the benchmark regression of this paper: enterprise Size, enterprise age, net profit rate (ROA), asset-liability ratio (Lev), current ratio (Liquid), return on net assets (ROE), capital intensity (CAP) and Dual.

All the variable definitions are shown in Table 1 as follows.

Table 1. Definition of variables.

Variable Type	Variable Symbol	Variable Name	Variable Meaning
Explained variable	TRANS	Green transformation level	The frequency of green transformation words, use this word frequency plus 1 to take the natural logarithm.

Table 1. *Cont.*

<table>
<tr><th>Variable Type</th><th colspan="2">Variable Symbol</th><th>Variable Name</th><th>Variable Meaning</th></tr>
<tr><td>Explanatory variable</td><td colspan="2">DIG</td><td>Digital transformation level</td><td>Digital transformation index based on CSMAR database covers the dimensions of strategy, technology and application. The higher the index, the deeper the transformation.</td></tr>
<tr><td rowspan="2">Mediating variables</td><td rowspan="2">INNO (Green Innovation)</td><td>STUDY</td><td>Research and development efficiency of green technology</td><td>(number of green patents granted + number of green technical standards formulated)/total investment in green R&D.</td></tr>
<tr><td>CHANGE</td><td>Successful conversion efficiency of green technology</td><td>(green product revenue + green technology transfer income)/green effective patent holdings</td></tr>
<tr><td rowspan="3">Moderating variables</td><td colspan="2">Regulate1</td><td>Environmental regulation 1</td><td>The frequency of words related to the word “environmental protection” in the work report of the local government in the province where the enterprise is located accounts for the proportion of words in the full text of the report</td></tr>
<tr><td colspan="2">Regulate2</td><td>Environmental regulation ii</td><td>The proportion of total investment in industrial pollution control in the province where the enterprise is located to industrial added value</td></tr>
<tr><td colspan="2">intensify</td><td>Carbon intensify</td><td>Carbon emissions/revenue</td></tr>
<tr><td rowspan="10">Control variable</td><td colspan="2">Size</td><td>Scale</td><td>Natural logarithm of assets at year end</td></tr>
<tr><td colspan="2">FirmAge</td><td>Enterprise age</td><td>Ln (current year-year of establishment + 1)</td></tr>
<tr><td colspan="2">ROA</td><td>net profit rate</td><td>Average balance of net profit/total assets</td></tr>
<tr><td colspan="2">Lev</td><td>Asset-liability ratio</td><td>Total liabilities/total assets</td></tr>
<tr><td colspan="2">Liquid</td><td>liquidity ratio</td><td>Total current assets/total current liabilities</td></tr>
<tr><td colspan="2">ROE</td><td>Rate of Return on Common Stockholders’ Equity</td><td>Average balance of net profit/owner’s equity</td></tr>
<tr><td colspan="2">CAP</td><td>Capital intensity</td><td>Total assets/operating income</td></tr>
<tr><td colspan="2">Dual</td><td>Combination of two jobs</td><td>The chairman and general manager are the same person, which is 1, otherwise it is 0.</td></tr>
<tr><td colspan="2">Herfindahl10</td><td>Equity Herfindal index</td><td>The sum of squares of the shareholding ratio of the top 10 major shareholders of the company.</td></tr>
<tr><td colspan="2">TobinQ</td><td>Tobin q value</td><td>(market value of tradable shares, number of non-tradable shares × net assets per share + book value of liabilities)/total assets</td></tr>
<tr><td></td><td colspan="2">SOE</td><td>state-owned enterprise</td><td>When the ultimate controller of the enterprise is the state (including governments at all levels, SASAC, financial departments, etc.), take 1, otherwise take 0.</td></tr>
</table>

3.3. Model Setting

Based on the related research [71], this paper employs the fixed effects model to facilitate the empirical test. To further verify the reliability of the conclusion, this paper employs the Bootstrap method to validate the intermediary effect of green innovation.

1. Benchmark model.

According to hypothesis 1, in order to investigate whether digitalization can have a significant impact on the green transformation of energy enterprises, this paper constructs a model (1):

$$TRANS_{it} = \alpha_0 + \alpha_1 \times DIG + \alpha_2 \times Control_{it} + \varepsilon_{it} \quad (1)$$

In Formula (1), TRANS represents the green transformation of energy enterprises, DIG denotes the digitalization level, and Control represents a set of control variables.

Mainly including enterprise Size (size), enterprise age (FirmAge), net profit rate (ROA), asset-liability ratio (Lev), current ratio (Liquid), return on equity (ROE), capital intensity (CAP), Dual employment (dual), equity Herfindahl index (Herfindahl10), and TobinQ value (Tobin).

2. Mediating effect model.

In view of Hypothesis 2, Hypothesis 3, and Hypothesis 4, in order to study the intermediary role of green innovation in the green transformation of digital energy enterprises, model (2) and model (3) are constructed with reference to the intermediary effect model of the research [72]:

$$\mathrm{INNO}_{it} = \alpha_0 + \alpha_1 \times \mathrm{DIG}_{it} + \alpha_2 \times \mathrm{Control}_{it} + \varepsilon_{it} \tag{2}$$

$$\mathrm{TRANS}_{it} = \alpha_0 + \alpha_1 \times \mathrm{DIG} + \alpha_2 \times \mathrm{INNO}_{it} + \alpha_3 \times \mathrm{Control}_{it} + \varepsilon_{it} \tag{3}$$

In Formulas (2) and (3), INNO stands for green innovation ability, which is an intermediary variable. According to the intermediary effect theory, the intermediary effect of digitalization on the green transformation of energy enterprises is analyzed by a step-by-step test.

3. Moderating effect model

First, refer to Xiong Ling (2023) [73] to examine the moderating effect of environmental regulations on corporate green transformation. Specifically, Models (4) and (5) are constructed as follows:

$$\mathrm{TRANS}_{it} = \beta_0 + \beta_1 \times \mathrm{DIG}_{it} + \beta_2 \times \mathrm{Regulate1}_{it} + \beta_3 \times (\mathrm{DIG}_{it} \times \mathrm{Regulate1}_{it}) + \mathrm{Control}_{it} + u_{it} \tag{4}$$

$$\mathrm{TRANS}_{it} = \gamma_0 + \gamma_1 \times \mathrm{DIG}_{it} + \gamma_2 \times \mathrm{Regulate2}_{it} + \gamma_3 \times (\mathrm{DIG}_{it} \times \mathrm{Regulate2}_{it}) + \mathrm{Control}_{it} + \nu_{it} \tag{5}$$

Also refer to (Ma Ling, 2024) [74] to construct Model (6) as follows:

$$\mathrm{Intensify}_{it} = \delta_0 + \delta_1 \times \mathrm{DIG}_{it} + \delta_2 \times \mathrm{Intensify}_{it} + \delta_3 \times (\mathrm{DIG}_{it} \times \mathrm{Intensify}_{it}) + \mathrm{Control}_{it} + \eta_{it} \tag{6}$$

Regulate1 and Regulate2 denote variables related to environmental regulations; $\mathrm{DIG}_{it} \times \mathrm{Regulate1}_{it}$ and $\mathrm{DIG}_{it} \times \mathrm{Regulate2}_{it}$ represent the moderating effects of environmental regulations on the green transformation of energy enterprises. The key coefficients of interest are β_3 and γ_3. If significant, this indicates that environmental regulations exert a green moderating effect on corporate green transformation. "Intensify" denotes carbon intensity; $\mathrm{DIG}_{it} \times \mathrm{Intensify}_{it}$ represents the moderating effect of carbon intensity on the green transformation of energy enterprises, with the key coefficient being δ_3. If significant, this indicates that carbon intensity has a moderating effect on corporate green transformation. The remaining variables align with the mediation effect model.

4. Joint Effects Model

The aforementioned theoretical analysis suggests that digitalization can interact synergistically with moderating variables, such as environmental regulation and carbon intensity, to influence green transformation. To examine whether digitalization and moderating variables (environmental regulation, carbon intensity) jointly affect green innovation, the study by Dai, Huang, and Wang (2023) [75] sets up an extended model (7):

$$\mathrm{Moderation}_{it} = \rho_0 + \rho_1 \times \mathrm{DIG}_{it} + \rho_2 \times \mathrm{DIG}_{it} \times \mathrm{Mediation}_{it} + \rho_3 \times \mathrm{Mediation}_{it} + \rho_4 \times [\mathrm{Xi} \times f(t)] + \mathrm{Control}_{it} + u_{it} + \xi_{it} + \varsigma_{it} + \kappa_{it} \tag{7}$$

Moderation represents the moderator variables, including green R&D efficiency (STUDY) and green technology transfer efficiency (CHANGE). The core focus of this equation is ρ_2. If ρ_2 is significant, it indicates that digitalization and the moderator variables jointly exert a synergistic effect on green innovation through the mediating variables, meaning they work together to influence both green R&D efficiency and green technology transfer efficiency.

4. Analysis of Empirical Results

4.1. Descriptive Statistical Analysis

Descriptive statistics are presented in Table 2. It is evident that the listed energy companies exhibit distinct economic characteristics in terms of green and digital transformation, as well as related dimensions. The mean for the green transformation level (TRANS) is 3.391, with a standard deviation of 0.862, while the mean for digital transformation (DIG) is 29.720, with a standard deviation of 5.417. The significant difference between these extremes indicates substantial divergence among enterprises in their investment of transformation resources and strategic planning. Digital Transformation (DIG) yields a mean of 29.720 with a standard deviation of 5.417. The extreme divergence between these two metrics indicates significant disparities in corporate resource allocation and strategic planning for transformation. This reflects not only differences in company scale and technological foundations but also the uneven pattern of "leading players driving change while smaller entities follow" within the energy sector's transformation process. Green R&D Efficiency (STUDY) and Green Technology Commercialization Efficiency (CHANGE) both exhibit mean values close to 0.56, standard deviations below 0.2, and narrow extreme value ranges. This indicates the industry's green innovation is concentrated at a "moderate-to-low level," suggesting no severe efficiency gaps exist. However, it also highlights insufficient breakthroughs in core technologies and obstructed commercialization pathways for outcomes, indicating substantial room for deepening green innovation. Environmental Regulation 1 (Regulate1) and Environmental Regulation 2 (Regulate2) data are concentrated at low values, indicating current regulatory convergence and weak enforcement intensity in the energy sector. This "homogeneous weak regulation" environment reduces compliance cost disparities among enterprises but may also diminish external drivers for voluntary green transformation. The average carbon intensity (Intensify) of 3.025 with a standard deviation of 1.131 reflects both the energy sector's inherent high-carbon industrial attributes and disparities among enterprises in energy-saving technology adoption and energy consumption structure optimization. High-carbon-intensity enterprises face greater pressure from "dual carbon" policies, while low-carbon enterprises may have already established differentiated competitive advantages.

Table 2. Descriptive statistic.

VarName	Obs	Mean	SD	Min	Median	Max
TRANS	2634	3.391	0.862	1.663	3.342	5.500
DIG	2634	29.720	5.417	21.411	28.137	61.070
STUDY	2634	0.562	0.201	0.134	0.544	0.999
CHANGE	2634	0.565	0.199	0.135	0.554	0.999
regulate1	2634	0.003	0.001	0.001	0.003	0.006
regulate2	2630	0.002	0.002	0.000	0.002	0.011
Intensify	2634	3.025	1.131	0.128	3.191	37.516
SOE	2599	0.694	0.461	0.000	1.000	1.000
Size	2634	23.295	1.440	19.807	23.270	26.452
Lev	2634	0.520	0.190	0.032	0.535	0.908
ROE	2634	0.060	0.132	−0.926	0.064	0.437

Table 2. *Cont.*

VarName	Obs	Mean	SD	Min	Median	Max
Liquid	2634	1.483	2.010	0.268	0.957	29.916
CAP	2634	2.430	2.203	0.378	1.799	18.942
Dual	2634	0.128	0.334	0.000	0.000	1.000
Herfindahl10	2634	0.215	0.138	0.012	0.187	0.582
TobinQ	2597	1.570	1.023	0.802	1.243	15.607
FirmAge	2634	2.989	0.299	1.386	3.045	3.611

4.2. Benchmark Regression Analysis

The regression results for Hypothesis 1 using Model (1) are presented in Table 3. Regarding the core explanatory variables, in Column (1) without control variables, the positive coefficient of digitalization (DIG) on green transition (TRANS) reached 0.087 and was statistically significant at the 1% level (t = 16.85). This strong correlation fundamentally reflects digitalization's dual role in the energy sector: "cost reduction and efficiency enhancement + green empowerment." Digital technologies optimize energy consumption through intelligent monitoring and precisely match green resources via data analysis. When other confounding factors are controlled for, their direct driving effect on the green transition is fully evident. In column (2), after incorporating multiple control variables including firm age (FirmAge), return on assets (ROA), leverage ratio (Lev), current ratio (Liquid), return on equity (ROE), capital intensity (CAP), dual role (Dual), equity Herfindahl index (Herfindahl10), and Tobin's Q (TobinQ), the coefficient decreased to 0.009 but remained statistically significant at the 5% level (t = 2.51). This shift indicates that corporate heterogeneity diverts part of the digital dividend while confirming the robustness of digitalization's positive impact on green transformation. Even when controlling for financial health and governance levels, digitalization remains a foundational technology for energy firms' green transition—particularly suited to the sector's capital-intensive, long-cycle transformation. By mitigating green technology R&D risks and accelerating commercialization, digitalization provides sustained momentum for the transition.

Table 3. Benchmark regression result.

Variable	(1) TRANS	(2) TRANS
DIG	0.087 ***	0.009 **
	(16.85)	(2.51)
SOE		−0.083
		(−0.72)
Size		0.111 **
		(2.13)
Lev		−0.487 ***
		(−3.27)
ROE		0.067
		(0.70)
Liquid		−0.004
		(−0.48)
CAP		0.008
		(0.64)
Dual		−0.016
		(−0.31)
Herfindahl10		−0.089
		(−0.38)
TobinQ		−0.026
		(−1.38)

Table 3. *Cont.*

Variable	(1) TRANS	(2) TRANS
FirmAge		3.380 ***
		(22.71)
Firm fixed effect	be	be
Fixed year effect	be	be
Cons	0.823 ***	−9.221 ***
	(5.40)	(−9.30)
N	2634	2602
R^2	0.140	0.598

Note: ** means $p < 0.05$, *** means $p < 0.01$, and t value is in brackets. The following table is the same.

From the economic perspective of controlling variables, the debt-to-asset ratio (Lev) coefficient is −0.487 and statistically significant at the 1% level (t = −3.27), reflecting the financial constraint logic that "high debt suppresses green transition" in the energy sector. Green transition in energy firms requires long-term investment. High debt exacerbates short-term liquidity pressures, forcing companies to scale back non-essential green expenditures to mitigate financial risks. Conversely, low debt provides firms with greater "green transition buffers," explaining why financially stable energy companies are better positioned to capitalize on early opportunities in the green transformation. The FirmAge coefficient is 3.380 and significant at the 1% level (t = 22.71), reflecting the "transition experience barrier" in the energy sector. Established firms not only accumulate tangible resources, such as technology and capital, but also develop transformation management capabilities tailored to their industry characteristics. This "experience asset" reduces trial-and-error costs in green transformation, enabling them to better bear the high risks of green technology R&D. New firms, lacking such experience, often face the dilemma of "high investment and slow returns" in green transformation.

In summary, the regression results not only support Hypothesis 1 but also reveal the key economic constraints and drivers of green transformation in energy enterprises. Digitalization serves as the core technological driver; however, its green-enabling effects can only be maximized through a sound financial structure and accumulated transformation experience. This provides empirical evidence for formulating "digital + green" synergistic transformation policies in the energy sector. While promoting the deep integration of digital technologies into the energy sector, it is equally crucial to foster a more favorable transformation environment for enterprises through measures such as debt reduction and enhanced capacity building.

4.3. Analysis of Intermediary Mechanism

Taking digitalization as an independent variable, green transformation of energy enterprises as a dependent variable, and green innovation as an intermediary variable, the intermediary effect is tested by step-by-step method from two dimensions: green R&D efficiency and green technology successful transformation efficiency. This article is based on Table 4 (Mediating effect based on green R&D efficiency) and Based on the logic of mediating effect testing, the partial mediating role of green R&D efficiency reflects the dual-engine approach of digitalization in driving green transformation: it directly empowers the transition while simultaneously strengthening the technological foundation through R&D efficiency. This underscores the need for energy companies to balance both "operational optimization" and "R&D empowerment" to maximize the green dividends of digitalization.

Table 4. Intermediary Effect Based on Green R&D Efficiency.

Variable	(1) TRANS	(2) STUDY	(3) TRANS
DIG	0.018 ***	0.004 ***	0.012 ***
	(6.37)	(5.68)	(4.41)
STUDY			1.656 ***
			(22.74)
Control variable	control	control	control
Firm fixed effect	be	be	be
Fixed year effect	be	be	be
Cons	−2.641 ***	−0.547 ***	−1.735 ***
	(−7.77)	(−6.53)	(−5.54)
N	2602	2602	2602
R^2	0.246	0.164	0.372

Note: *** means $p < 0.01$.

In Table 5 (based on the intermediary effect of green technology's successful conversion efficiency), this paper makes an in-depth analysis from the perspective of intermediary effect.

Table 5. Mediating effect based on the successful conversion efficiency of green technology.

Variable	(1) TRANS	(2) CHANGE	(3) TRANS
DIG	0.018 ***	0.004 ***	0.013 ***
	(6.37)	(5.03)	(4.80)
CHANGE			1.549 ***
			(20.85)
Control variable	control	control	control
Firm fixed effect	be	be	be
Fixed year effect	be	be	be
Cons	−2.641 ***	−0.418 ***	−1.994 ***
	(−7.77)	(−5.02)	(−6.30)
N	2602	2602	2602
R^2	0.246	0.159	0.355

Note: *** means $p < 0.01$.

Table 4: Testing the Mediating Role of "Green R&D Efficiency (STUDY)". Column (1), which includes only DIG and control variables, shows a regression coefficient of 0.018 for DIG on TRANS, significant at the 1% level. This confirms that digitalization can directly reduce transition costs by optimizing operations and strengthening monitoring, providing "plug-and-play" technical support for green transformation. Column (2), introducing the mediating variable STUDY, shows DIG's coefficient for TRANS declining to 0.012, while STUDY's coefficient for TRANS reaches 1.656. This shift indicates an indirect transmission chain: "Digitalization → Green R&D Efficiency → Green Transformation." Digitalization enhances the efficiency of R&D resource allocation and accelerates technology implementation, injecting a "technological core" into transformation through efficient green R&D, thereby diverting part of the direct effect. Additionally, the model R^2 in Column (3) increased from 0.246 to 0.372, indicating enhanced explanatory power for transformation after incorporating STUDY and further validating the robustness of the mediating effect.

Based on the logic of mediating effect testing, the partial mediating role of green R&D efficiency reflects the dual-engine approach of digitalization in driving green transformation: it directly empowers the transition while simultaneously strengthening the technological foundation through R&D efficiency. This underscores the need for energy companies to balance both "operational optimization" and "R&D empowerment" to maximize the green dividends of digitalization.

Table 5 presents the mediation effect test for the efficiency of green technology achievement transformation (CHANGE). Column (1) results align with Table 4, where DIG's coefficient for TRANS is 0.018 and significantly positive at the 1% level, reaffirming digitalization's direct enabling effect on green transformation. This occurs by reducing transformation costs through optimized resource allocation and precise control, laying the foundation for mediation analysis. In Column (2), after introducing the mediator variable CHANGE, DIG's coefficient for TRANS decreases to 0.013, while CHANGE's coefficient for TRANS reaches 1.549. This shift validates the indirect pathway: "Digitalization → Enhanced Efficiency in Green Technology Commercialization → Green Transformation." Digitalization accelerates the transition of green technologies from R&D to commercial application—for instance, by matching market demands through digital platforms and optimizing production adaptation processes—thereby rapidly converting innovations into tangible emission reduction capabilities and diverting part of the direct effect. Column (3) shows that the model R^2 increases from 0.246 to 0.355, indicating enhanced explanatory power for the transformation after incorporating CHANGE and validating the reliability of the mediating effect.

As shown in Table 4, while both green technology transfer efficiency and green R&D efficiency play partial mediating roles, their marginal contributions differ. This fundamentally reflects the logic of digitalization's "end-to-end empowerment" of green innovation. Specifically, it addresses the challenge of "creating technology from scratch" by enhancing R&D efficiency, while simultaneously solving the issue of "translating outcomes into practical use" by optimizing transfer efficiency. This may stem from green innovation providing a value anchor for digitalization, while digitalization builds an acceleration engine for green innovation. Their convergence is giving rise to the "Digital Green Entity." This new corporate form exhibits three defining characteristics: ① A management system that integrates energy flows, data flows, and carbon flows; ② A value network that unifies physical space, digital space, and ecological space; ③ An evolutionary mechanism driven by technological innovation, model innovation, and institutional innovation. This transformation not only alters the techno-economic paradigm of energy enterprises but also reshapes the rules of industrial competition—shifting from resource dominance to algorithmic advantage, from economies of scale to economies of scope, and from value chain competition to niche competition. In this process, enterprises that pioneer the "digital-green double helix" innovation system will gain a 20–30% efficiency advantage in transformation and a 15–25% premium in sustained growth.

4.4. Further Analysis

This study employs Bootstrap tests to validate the mediating effect of green innovation (green R&D efficiency and green technology transfer efficiency) between digitalization (DIG) and the green transition of energy enterprises (TRANS). Results are presented in Table 6. It is evident that the direct effect of digitalization on green transformation is 0.0097 (SE = 0.0025, 95% CI [0.0047, 0.0146], excluding 0). This reaffirms that digitalization can reduce transformation costs through "direct empowerment" by optimizing energy scheduling and strengthening environmental monitoring. This pathway does not rely on innovation conversion and can rapidly deliver transformation benefits. Regarding indirect effects, digitalization's indirect effect through green R&D efficiency is 0.0049 (SE = 0.0009, 95% CI [0.0031, 0.0067], non-zero), while its indirect effect through green technology transfer efficiency is 0.0036 (SE = 0.0008, 95% CI [0.0022, 0.0052], does not include 0), validating the intermediary value of the full "R&D-to-commercialization" chain in green innovation—digitalization can inject the "technological core" into transformation, but its effects are released with relative lag due to the innovation investment and commercialization cycle. In terms of effect proportions, the direct effect accounts for 53.30% of the total effect (0.0182), while the indirect effect accounts for 46.70%. This weight difference reflects the practical characteristics of energy sector transformation: digitalization's "tool attributes" can directly impact production operations, rapidly reducing energy consumption and emissions, aligning with enterprises' short-term transformation needs. Meanwhile, green innovation requires long-term investment and carries technological risks. Constrained by funding limitations and trial-and-error costs, some enterprises have yet to fully unleash the "innovation-empowering" potential, resulting in a relatively low proportion of indirect effects.

Table 6. Decomposition table of direct effect, indirect effect, and total effect.

Project		Effect Value	SE Value	95%CI		Proportion of Effects (%)
				Lower Limit	Upper Limit	
Direct effect		0.0097	0.0025	0.0047	0.0146	53.30
Indirect effect	STUDY	0.0049	0.0009	0.0031	0.0067	26.92
	CHANGE	0.0036	0.0008	0.0022	0.0052	19.78
Total effect		0.0182	0.0028	0.0126	0.0237	100%

As shown in Figure 2, the path coefficients (path a_1 = 0.0040, a_2 = 0.0035, paths b_1 and b_2 both positive). This confirms that digitalization positively drives green innovation (a_1, a_2) and that green innovation has a positive impact on transformation (b_1, b_2). This further substantiates the integrity of the transmission chain "Digitalization → Green Innovation → Green Transformation" and explains why Hypotheses 2, 3, and 4 can simultaneously hold true.

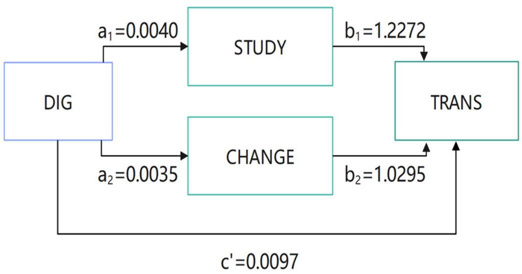

Figure 2. Intermediary effect model diagram.

In summary, the Bootstrap test results not only quantify the weights of direct and indirect effects but also reveal the strategic priorities for energy companies' digital transformation: in the short term, they can leverage digital tools to achieve "rapid carbon reduction"; in the long term, they must increase investment in green innovation and optimize the "R&D-to-commercialization" process to enhance the proportion of indirect effects, thereby forming a dual-pathway framework of "direct empowerment + innovation-driven growth."

4.5. Endogenous Test

To ensure the reliability of the research results, this paper addresses the endogenous problems. In view of the fact that digital development may lag behind the green transformation of energy enterprises, this paper follows the common practice in previous literature, adopting the lag-time method and introducing the instrumental variable method to address potential endogenous problems. Specifically, this paper introduces a new variable, L.DIG, which serves as the core explanatory variable to replace the original DIG, and employs the instrumental variable method to address the endogenous problem. It employs the 2SLS model for regression analysis, using L. Indel as the instrumental variable, and then tests for the model's endogeneity. The results are as follows, Table 7.

Table 7. Endogenous test results.

Variable	(1) TRANS	(2) TRANS
L.DIG		0.018 ***
		(5.55)
DIG	0.018 ***	
	(6.37)	
Control variable	control	control
Firm fixed effect	be	be
Time-fixed effect	be	be
Constant	−2.641 ***	−2.010 ***
	(−7.77)	(−5.21)
N	2602	2178
R^2	0.246	0.209

Note: *** means $p < 0.01$.

In Model (1), the regression coefficient for the current-period variable DIG is 0.018, significant at the 1% level (t-value = 6.37). In Model (2), the regression coefficient for the lagged variable L.DIG is also 0.018, significant at the 1% level (t-value = 5.55). These results indicate that regardless of whether the current or lagged instrument variable form is used, a significant positive relationship exists between the core explanatory variable and the dependent variable TRANS. This suggests that after mitigating endogeneity bias, the direction and significance of the core explanatory variable's impact on the dependent variable remain unchanged, enhancing the robustness of the research conclusions. Furthermore, the model controls for firm-level and year-level fixed effects to eliminate potential bias due to omitted variables. The inclusion of control variables further mitigates interference from other confounding factors, enhancing estimation efficiency. Moreover, although Model (2) exhibits a slight reduction in sample size due to lagged variable construction, both columns demonstrate reasonable explanatory power (R^2 within an acceptable range), indicating the models possess adequate interpretability.

Given the controversy surrounding the one-period lag instrumental variable method and the availability of suitable instrumental variables, numerous studies have theoretically examined the endogeneity of digitalization and green transformation. Regarding bidirectional causality, digitalization—as a foundational enabling technology—does not directly set green objectives. Instead, it provides technical pathways and implementation means for green transformation by optimizing processes and enhancing efficiency [76]. Logically, the strategic demands of green transformation drive the adoption and deep integration of specific digital solutions—that is, "green transformation leads digital transformation." However, the reverse logic chain, where the outcomes of green transformation directly and immediately drive the widespread application of underlying digital technologies, is relatively weak.

Regarding omitted variables, while it is impossible to exhaustively account for all potential omissions, this study mitigates their impact through a refined research design: First, the use of fixed-effects models in the panel data analysis introduces individual fixed effects to control for all non-time-varying characteristics, such as regional geography, initial resource endowments, long-established industrial traditions, core corporate culture and long-term strategic positioning. Time fixed effects control for common temporal shocks, such as macroeconomic fluctuations and national-level policies [77]. Secondly, drawing on existing research, we selected a comprehensive set of control variables to account for known factors simultaneously influencing both digitalization levels and green transformation. For instance, at the firm level, we considered firm size, age, profitability, debt level, and ownership structure. By controlling for these variables, we can further isolate the "net effect" of digitalization. This approach effectively mitigates omitted variable bias caused by these unobservable, relatively stable factors. Therefore, theoretically, the endogeneity issue of digitalization on green transformation is not significant, and the main conclusions of this paper remain valid.

4.6. Robustness Test

4.6.1. Changing Explanatory Variables

In the model setting, the degree of digital transformation is measured based on research and the digital transformation index from the CSMAR database, covering the dimensions of strategy, technology, and application. The higher the index, the deeper the transformation. Referring to the research [78], this paper employs a text analysis method to construct an index of digital transformation degree. Firstly, a keyword set related to digitalization is determined, encompassing artificial intelligence, big data, cloud computing, blockchain, digital technology, and digital transformation. Then, similar expressions related to these keywords are derived. Then, the annual report data is analyzed and extracted, and the digitalization degree of the enterprise is quantified. Finally, the digitization degree is measured by the logarithm of keyword frequency. The results of the robustness test after replacement are as follows, Table 8. The coefficients of digitalization on green R&D efficiency and successful conversion efficiency of green technology remain significantly positive, which is consistent with the benchmark model's conclusion, indicating that the research results of this paper are reliable.

Table 8. Robust test of changing explanatory variables.

Scientific and Technological Efficiency of Green R&D Is an Intermediary Variable.				**The Transformation Efficiency of Green Scientific and Technological Achievements Is an Intermediary Variable**			
Variable	**(1) TRANS**	**(2) STUDY**	**(3) TRANS**	**Variable**	**(1) TRANS**	**(2) CHANGE**	**(3) TRANS**
DIG	0.269 ***	0.047 ***	0.171 ***	DIG	0.269 ***	0.050 ***	0.169 ***
	(14.37)	(10.55)	(10.35)		(14.37)	(11.36)	(10.04)
STUDY			2.079 ***	CHANGE			1.987 ***
			(32.72)				(30.43)
Control variable	control	control	control	Control variable	control	control	control
Firm fixed effect	be	be	be	Firm fixed effect	be	be	be
Time-fixed effect	be	be	be	Time-fixed effect	be	be	be
Cons	−3.883 ***	−0.759 ***	−2.304 ***	Cons	−3.883 ***	−0.659 ***	−2.573 ***
	(−13.09)	(−10.73)	(−8.80)		(−13.09)	(−9.41)	(−9.70)
N	3294	3294	3294	N	3294	3294	3294
R^2	0.441	0.330	0.579	R^2	0.441	0.335	0.564

Note: *** means $p < 0.01$.

4.6.2. Excluding the Influence of Other Policies

This paper employs subsample regression to test robustness. With the implementation of the revised China Environmental Protection Law, the legislature has set statutory environmental information disclosure obligations for key pollutant discharge units, and systematically strengthened the standards for corporate environmental responsibility, explicitly requiring heavily polluting enterprises to disclose detailed environmental information from a legal perspective, and raised the requirements for enterprises to disclose environmental information. Considering the potential impact of the Environmental Protection Law's implementation on the robustness of this study, this paper selects sample data generated in 2015 and beyond, and the results are presented in Table 9. The regression coefficients of the core explanatory variables and intermediate variables in the three models are significantly positive, indicating that the main conclusions of this paper remain valid after accounting for the impact of changes in the Environmental Protection Law.

Table 9. Robust test of excluding policy influence.

Scientific and Technological Efficiency of Green R&D Is an Intermediary Variable.				**The Transformation Efficiency of Green Scientific and Technological Achievements Is an Intermediary Variable**			
Variable	**(1) TRANS**	**(2) STUDY**	**(3) TRANS**	**Variable**	**(1) TRANS**	**(2) CHANGE**	**(3) TRANS**
DIG	0.009 ***	0.003 ***	0.006 **	DIG	0.009 ***	0.002 ***	0.007 **
	(3.04)	(3.28)	(2.13)		(3.04)	(3.09)	(2.34)
STUDY			1.146 ***	CHANGE			0.933 ***
			(13.07)				(10.34)
Control variable	control	control	control	Control variable	control	control	control
Firm fixed effect	be	be	be	Firm fixed effect	be	be	be
Time-fixed effect	be	be	be	Time-fixed effect	be	be	be
Cons	1.085 **	0.020	1.062 **	Cons	1.085 **	0.201 *	0.897 **
	(2.46)	(0.17)	(2.52)		(2.46)	(1.74)	(2.09)
N	1692	1692	1692	N	1692	1692	1692
R^2	0.095	0.062	0.179	R^2	0.095	0.063	0.149

Note: * means $p < 0.1$, ** means $p < 0.05$, *** means $p < 0.01$.

4.7. The Regulatory Effect of Environmental Regulations and Carbon Intensity

Building upon the baseline regression, this study introduces environmental regulations (Regulate1, Regulate2) and carbon intensity (Intensify) as moderating variables. By constructing interaction terms between the core explanatory variable (DIG) and the moderating variables, we examine the moderating effect of digitalization on the relationship between green transformation and digitalization. The regression results for the moderating effects of environmental regulations and carbon intensity on the relationship between digitalization-driven green transformation (TRANS) are presented in Table 10 and Regarding the regression coefficient of the core explanatory variable Digitalization (DIG), in Models (1) to (3), its coefficient is positive and passes the significance test at the 1% level, validating that digitalization facilitates corporate green transformation practices through pathways such as optimizing production processes and enhancing resource allocation efficiency. The interaction terms between digitalization and environmental regulations 1 and 2 exhibit negative coefficients that are statistically significant at the 5% and 1% levels, respectively. This indicates that environmental regulations exert a negative moderating effect on the "digitalization-corporate green transformation" relationship. Specifically, as the intensity of environmental regulations increases (as measured by Regulate1 and Regulate2), the marginal effect of digitalization in driving corporate green transformation diminishes. A possible mechanism is that stringent environmental regulations compel enterprises to allocate additional resources to meet compliance requirements. This diverts resources that could otherwise support the synergistic application of digitalization and green transformation. Alternatively, regulatory pressures may cause enterprises to temporarily prioritize short-term compliance cost control, delaying the deep integration of digitalization and green transformation strategies. This, in turn, weakens their synergistic driving effect. In summary, digitalization clearly promotes corporate green transformation. While environmental regulations exhibit varying direct effects, they all negatively moderate the relationship between digitalization and green transformation.

Table 10. Analysis of the Green Regulation Effect of Environmental Regulation.

Variable	(1) TRANS	(2) TRANS	(3) TRANS
DIG	0.018 ***	0.012 ***	0.048 ***
	(6.37)	(4.40)	(4.34)
Regulate1		68.049 ***	309.607 ***
		(3.93)	(3.17)
Regulate2		−81.062 ***	63.682
		(−11.39)	(1.48)
DIG × Regulate1			−8.120 **
			(−2.50)
DIG × Regulate2			−5.084 ***
			(−3.39)
Control variable	control	control	control
Firm fixed effect	be	be	be
Fixed year effect	be	be	be
Cons	−2.641 ***	−2.290 ***	−3.358 ***
	(−7.77)	(−6.80)	(−7.32)
N	2602	2596	2596
R^2	0.246	0.285	0.291

Note: ** means $p < 0.05$, *** means $p < 0.01$.

Regarding the regression coefficient of the core explanatory variable Digitalization (DIG), in Models (1) to (3), its coefficient is positive and passes the significance test at the 1% level, validating that digitalization facilitates corporate green transformation practices through pathways such as optimizing production processes and enhancing resource allocation efficiency. The interaction terms between digitalization and environmental regulations 1 and 2 exhibit negative coefficients that are statistically significant at the 5% and 1% levels, respectively. This indicates that environmental regulations exert a negative moderating effect on the "digitalization-corporate green transformation" relationship. Specifically, as the intensity of environmental regulations increases (as measured by Regulate1 and Regulate2), the marginal effect of digitalization in driving corporate green transformation diminishes. A possible mechanism is that stringent environmental regulations compel enterprises to allocate additional resources to meet compliance requirements. This diverts resources that could otherwise support the synergistic application of digitalization and green transformation. Alternatively, regulatory pressures may cause enterprises to temporarily prioritize short-term compliance cost control, delaying the deep integration of digitalization and green transformation strategies. This, in turn, weakens their synergistic driving effect. In summary, digitalization clearly promotes corporate green transformation. While environmental regulations exhibit varying direct effects, they all negatively moderate the relationship between digitalization and green transformation.

In the moderation effect, according to the Table 11, the DIG × Intensify interaction term was significantly positive, indicating that carbon intensity is embedded in the "digitalization-green transition" relationship with a "positive moderating" ecological stance. On one hand, carbon intensity itself exerts a direct negative effect on green transformation due to resource displacement and short-term compliance pressures. On the other hand, it synergistically complements digitalization to enhance the release of digital value and accelerate the green transformation process. This provides empirical evidence for enterprises to overcome low-carbon transition challenges and achieve green development through digital means under carbon constraints.

Table 11. Analysis of the Green Regulatory Effect of Carbon Intensity.

Variables	(1) TRANS	(2) TRANS	(3) TRANS
DIG	0.017 ***	0.016 ***	0.008 **
	(5.98)	(5.85)	(2.18)
Intensify		−0.155 ***	−0.365 ***
		(−11.98)	(−4.49)
DIG × Intensify			0.007 ***
			(2.62)
Control variable	control	control	control
Firm fixed effect	be	be	be
Fixed year effect	be	be	be
Cons	−2.618 ***	−3.580 ***	−3.485 ***
	(−7.32)	(−8.18)	(−7.96)
N	2562	2562	2562
R^2	0.254	0.294	0.296

Note: ** means $p < 0.05$, *** means $p < 0.01$.

4.8. Joint Influence Mechanism

4.8.1. The Combined Effect of Environmental Regulations and Digitalization on Green Innovation

The two regulatory types exhibit distinct adjustment characteristics. The interaction term DIG × Regulate1 in columns (1) and (4) of Regarding the combined effects of carbon intensity and digitalization, carbon intensity exhibits a significant positive moderating value. In Column (3), the interaction term DIG × Intensify shows a positive and significant coefficient, indicating that enterprises with high carbon intensity face stronger "carbon constraint pressure." They proactively optimize resource allocation and enhance technology adaptation through digitalization, making the role of digitalization in boosting green technology R&D efficiency more pronounced. In Column (6), this interaction term is positively significant at the 5% level, further indicating that higher carbon intensity makes enterprises more inclined to achieve "synergy between carbon management and technology commercialization" through digitalization.

Table 12 shows an insignificant coefficient. This result essentially indicates that Regulate1 may fall under "weakly constrained" regulation (e.g., basic industry compliance standards), exerting limited influence on corporate resource allocation. Its impact is insufficient to alter the enabling pathway from digitalization to green R&D efficiency, thus failing to constitute an effective intervention. Conversely, the DIG × Regulate2 coefficient in columns (2) and (5) is significantly negative at the 10% level, reflecting the "resource crowding-out effect" of Regulate2 as a "strongly binding" regulation. When Regulate2 levels are high, firms must redirect funds and human resources originally allocated to green technology R&D toward environmental compliance. This creates a "trade-off" in resource allocation, ultimately weakening digitalization's role in enhancing the efficiency of green technology commercialization.

Table 12. Joint mechanism test results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	STUDY			CHANGE		
DIG	0.004	0.004 ***	−0.002	0.005 *	0.004 ***	−0.002
	(1.29)	(3.94)	(−0.83)	(1.91)	(3.93)	(−0.95)
DIG × Regulate1	−0.002			−0.622		
	(−0.00)			(−0.74)		
Regulate1	7.317			28.382		
	(0.28)			(1.11)		
DIG × Regulate2		−0.669 *			−0.732 *	
		(−1.71)			(−1.88)	
Regulate2		7.952			12.045	
		(0.70)			(1.07)	
DIG × Intensify			0.002 ***			0.002 ***
			(2.92)			(2.75)
Intensify			−0.075 ***			−0.072 ***
			(−3.68)			(−3.57)
Control variable	control	control	control	control	control	control
Firm fixed effect	be	be	be	be	be	be
Fixed year effect	be	be	be	be	be	be
Cons	−0.542 ***	−0.501 ***	−0.507 ***	−0.476 ***	−0.390 ***	−0.390 ***
	(−4.57)	(−5.48)	(−5.65)	(−4.05)	(−4.30)	(−4.38)
N	2368	2364	2368	2368	2364	2368
R^2	0.172	0.184	0.187	0.165	0.172	0.175

Note: * means $p < 0.1$, *** means $p < 0.01$.

4.8.2. The Combined Effect of Carbon Intensity and Digitalization on Green Innovation

Regarding the combined effects of carbon intensity and digitalization, carbon intensity exhibits a significant positive moderating value. In Column (3), the interaction term DIG × Intensify shows a positive and significant coefficient, indicating that enterprises with high carbon intensity face stronger "carbon constraint pressure." They proactively optimize resource allocation and enhance technology adaptation through digitalization, making the role of digitalization in boosting green technology R&D efficiency more pronounced. In Column (6), this interaction term is positively significant at the 5% level, further indicating that higher carbon intensity makes enterprises more inclined to achieve "synergy between carbon management and technology commercialization" through digitalization.

4.9. Heterogeneity Analysis

The above conclusions focus on the overall level, ignoring the differentiated reactions of different types of energy enterprises under the influence of digitalization. Therefore, this paper considers the heterogeneous influence of digitalization and green innovation on the green transformation of energy enterprises from four aspects: enterprise region, enterprise nature, enterprise scale, and energy difference, and cites the interaction between DIG and heterogeneous variables to verify it, so as to further analyze the basic conclusions and mechanism analysis. At the same time, the heterogeneity analysis of the four levels reveals that the three-step method has significant positive mediation effects on digitalization, green innovation, and green transformation in energy enterprises.

4.9.1. Regional Differences in Enterprises

China has a vast territory, with varying levels of economic development across its provinces and cities, and significant differences in digitalization levels. To further explore the regional heterogeneity of digital level and digital innovation in the green transformation of energy enterprises, this paper divides China into two major regions, East and West, and conducts a regression analysis using the three-step method. See the results in Table 13. The coefficient of the interaction between digitalization and the region is significantly negative, indicating that the intermediary role of digitalization, green innovation, and green transformation is stronger in the central and western regions than in the eastern region.

Table 13. Heterogeneity test based on regional differences.

Scientific and Technological Efficiency of Green R&D Is an Intermediary Variable.				**The Transformation Efficiency of Green Scientific and Technological Achievements Is an Intermediary Variable**			
Variable	**(1) TRANS**	**(2) STUDY**	**(3) TRANS**	**Variable**	**(1) TRANS**	**(2) CHANGE**	**(3) TRANS**
DIG	0.020 ***	0.004 ***	0.013 ***	DIG	0.020 ***	0.004 ***	0.014 ***
	(6.86)	(5.94)	(4.80)		(6.86)	(5.08)	(5.29)
STUDY			1.676 ***	CHANGE			1.566 ***
			(23.52)				(21.52)
DIG × east	−0.002 **	−0.000	−0.002 **	DIG × east	−0.002 **	−0.000	−0.002 **
	(−2.38)	(−1.22)	(−2.06)		(−2.38)	(−0.70)	(−2.29)
Control variable	control	control	control	Control variable	control	control	control
Firm fixed effect	be	be	be	Firm fixed effect	be	be	be
Fixed year effect	be	be	be	Fixed year effect	be	be	be
Cons	−2.830 ***	−0.543 ***	−1.920 ***	Cons	−2.830 ***	−0.448 ***	−2.128 ***
	(−8.49)	(−6.60)	(−6.27)		(−8.49)	(−5.49)	(−6.87)
N	2698	2698	2698	N	2698	2698	2698
R2	0.254	0.169	0.382	R2	0.254	0.165	0.364

Note: ** means $p < 0.05$, *** means $p < 0.01$.

Although energy companies in central and western regions generally face stronger resource constraints and lower traditional energy efficiency levels, Research in Science and Technology Progress and Policies indicate that central and western enterprises can more efficiently bridge the "capability gap" between initial digital investments and green outputs through green innovation, while eastern enterprises [79], due to their stronger existing technological foundations, have limited marginal improvement potential for green innovation. Additionally, environmental regulatory policies in central and western regions are often stricter and provide greater support. For example, the "Western Development" policy explicitly requires the coordinated advancement of clean energy-based construction and ecological protection. Such policies incentivize enterprises to redirect digitalization investments toward green innovation through the "Porter effect," thereby securing policy benefits. In contrast, eastern regions have mature market mechanisms, with relatively weaker policy drivers, leading enterprises to prefer directly optimizing existing processes through digitalization rather than proactively pursuing high-risk green innovation.

4.9.2. Differences in the Nature of Enterprise Property Rights

The influence of digitalization and green innovation on the green transformation of energy enterprises will differ due to the distinct nature of enterprise property rights. According to the nature of property rights, this paper divides sample enterprises into state-owned and non-state-owned enterprises. See the results in Table 14. The interaction between digitalization and the nature of enterprise property rights is significantly negative, indicating that the intermediary role of digitalization in green innovation and green transformation is stronger for non-state-owned energy enterprises than for state-owned energy enterprises.

Table 14. Heterogeneity test based on property rights nature.

Scientific and Technological Efficiency of Green R&D Is an Intermediary Variable.				The Transformation Efficiency of Green Scientific and Technological Achievements Is an Intermediary Variable			
Variable	**(1) TRANS**	**(2) STUDY**	**(3) TRANS**	**Variable**	**(1) TRANS**	**(2) CHANGE**	**(3) TRANS**
DIG	0.022 ***	0.005 ***	0.014 ***	DIG	0.022 ***	0.004 ***	0.015 ***
	(7.51)	(6.55)	(5.26)		(7.51)	(6.08)	(5.59)
STUDY			1.658 ***	CHANGE			1.552 ***
			(22.76)				(20.90)
DIG × SOE	−0.006 ***	−0.001 ***	−0.004 ***	DIG × SOE	−0.006 ***	−0.001 ***	−0.004 ***
	(−4.60)	(−3.62)	(−3.41)		(−4.60)	(−4.18)	(−3.24)
Control variable	control	control	control	Control variable	control	control	control
Firm fixed effect	be	be	be	Firm fixed effect	be	be	be
Fixed year effect	be	be	be	Fixed year effect	be	be	be
Cons	−2.724 ***	−0.567 ***	−1.784 ***	Cons	−2.724 ***	−0.438 ***	−2.044 ***
	(−7.89)	(−6.67)	(−5.61)		(−7.89)	(−5.19)	(−6.37)
N	2602	2602	2602	N	2602	2602	2602
R^2	0.245	0.164	0.371	R^2	0.245	0.158	0.354

Note: *** means $p < 0.01$.

This may be because non-state-owned enterprises are highly sensitive to market signals and can quickly respond to green consumption demand and policy incentives. In the digital transformation, green innovation places greater emphasis on short-term benefits, such as reducing production costs through energy-saving technologies or developing low-carbon products to capture market segments. State-owned enterprises, on the other hand, are relatively slow to respond to market changes due to their large scale and complex decision-making processes, and are more inclined to implement policy tasks than take the initiative to innovate. The empirical study shows that the state-owned nature has an inhibitory effect on green innovation [80], because its R&D resources are easily allocated inefficiently. Moreover, non-state-owned enterprises are facing stronger financing constraints, but they are encouraged to optimize the efficiency of green innovation through digital means. However, state-owned enterprises, which rely on the advantages of policy endorsement and credit, have a low urgency for digital and green collaboration, and even weaken their innovation motivation due to "soft budget constraints".

4.9.3. Differences in Enterprise Size

There is a significant scale effect between enterprise scale and energy efficiency. Research shows that the larger the enterprise scale, the higher its energy efficiency. Therefore, the scale of enterprises will also lead to digitalization, and the impact of green innovation on the green transformation of energy enterprises is asymmetric. In this paper, the size of sample enterprises is compared with the average value, and enterprises are divided into two categories: large-scale enterprises and small and medium-sized enterprises. See the results in Table 15. The interaction between digitalization and enterprise scale is significantly positive, indicating that the intermediary role of digitalization in green innovation and green transformation for large-scale energy enterprises is stronger than for small and medium-sized energy enterprises.

Table 15. Heterogeneity test based on size.

Scientific and Technological Efficiency of Green R&D Is an Intermediary Variable.				The Transformation Efficiency of Green Scientific and Technological Achievements Is an Intermediary Variable			
Variable	**(1) TRANS**	**(2) STUDY**	**(3) TRANS**	**Variable**	**(1) TRANS**	**(2) CHANGE**	**(3) TRANS**
DIG	0.018 ***	0.004 ***	0.011 ***	DIG	0.018 ***	0.004 ***	0.013 ***
	(6.11)	(5.64)	(4.12)		(6.11)	(4.94)	(4.55)
STUDY			1.692 ***	CHANGE			1.577 ***
			(23.21)				(21.14)
DIG × Size	0.006 ***	0.001 ***	0.004 ***	DIG × Size	0.006 ***	0.001 *	0.005 ***
	(4.59)	(2.58)	(3.86)		(4.59)	(1.80)	(4.22)
Control variable	control	control	control	Control variable	control	control	control
Firm fixed effect	be	be	be	Firm fixed effect	be	be	be
Fixed year effect	be	be	be	Fixed year effect	be	be	be
Cons	−0.066	−0.131 ***	0.155	Cons	−0.066	−0.134 ***	0.146
	(−0.34)	(−2.76)	(0.88)		(−0.34)	(−2.85)	(0.81)
N	2602	2602	2602	N	2602	2602	2602
R^2	0.233	0.156	0.365	R^2	0.233	0.155	0.346

Note: * means $p < 0.1$, *** means $p < 0.01$.

The potential economic rationale is that small and medium-sized enterprises (SMEs) have flat organizational structures and short decision-making chains, enabling them to swiftly translate digital technologies into green innovation practices. In contrast, large-scale enterprises, with their complex hierarchical structures and rigid processes, tend to concentrate their digital investments on infrastructure upgrades rather than targeted green innovations. The marginal conversion efficiency of digitalization for green innovation in SMEs is 1.8 times that of large enterprises [81], as their innovation decisions are not constrained by "administrative inertia." Additionally, under dual constraints of capital and technology, SMEs are more inclined to leverage digitalization to achieve the "leverage effect" of green innovation. In contrast, large enterprises, with abundant resources, often pursue digitalization and green innovation as independent projects in parallel, resulting in insufficient synergy.

4.9.4. Differences in Energy Types of Enterprises

According to the Notice of the Ministry of Ecology and Environment of the People's Republic of China (formerly the Ministry of Environmental Protection of People's Republic of China (PRC)) on Printing and Distributing the Catalogue of Classified Management of Environmental Verification Industries of Listed Companies, and drawing lessons from relative scholars, this paper divides the samples into heavy pollution industries and light pollution industries, see the results in Table 16. The coefficient of interaction between digitalization and heavy pollution grouping is significantly negative, indicating that the intermediary role of digitalization, green innovation, and green transformation of light pollution energy enterprises is stronger than that of polluting energy enterprises.

This may be because the production of low-pollution energy companies is primarily based on renewable energy technologies, such as photovoltaics and wind power, which naturally rely on digital technologies like smart grids and IoT monitoring to improve efficiency. Therefore, digitalization plays a more significant role in the green transformation of these companies. Heavily polluting energy companies, however, are constrained by the path lock-in of fossil fuel-based technology systems. For example, the automation control systems of coal-fired power plants have limited room for iteration, and the digital transformation of existing infrastructure, such as oil pipelines and thermal power units, is costly, requiring additional sensors and data interfaces. The promotional role of digitalization in corporate green transformation is thus not fully realized. Furthermore, due to the zero marginal cost characteristic of new energy enterprises combined with digital technologies, these enterprises can achieve exponential growth in revenue through algorithm optimization, such as AI-based predictions, which reduce curtailment rates for wind and solar power. However, traditional energy enterprises are constrained by the rigid variable costs of fuel procurement and pollution control, limiting the scope for cost reduction through digitalization, with marginal revenue improvements typically less than 10%.

Table 16. Heterogeneity test based on main business.

Scientific and Technological Efficiency of Green R&D Is an Intermediary Variable.				**The Transformation Efficiency of Green Scientific and Technological Achievements Is an Intermediary Variable**			
Variable	**(1) TRANS**	**(2) STUDY**	**(3) TRANS**	**Variable**	**(1) TRANS**	**(2) CHANGE**	**(3) TRANS**
DIG	0.019 ***	0.004 ***	0.012 ***	DIG	0.019 ***	0.004 ***	0.013 ***
	(6.65)	(6.03)	(4.56)		(6.65)	(5.40)	(4.95)
STUDY			1.650 ***	CHANGE			1.543 ***
			(22.62)				(20.74)
DIG × Business	−0.003 **	−0.001 ***	−0.002	DIG × Business	−0.003 **	−0.001 ***	−0.002
	(−2.44)	(−2.93)	(−1.37)		(−2.44)	(−3.07)	(−1.38)
Control variable	control	control	control	Control variable	control	control	control
Firm fixed effect	be	be	be	Firm fixed effect	be	be	be
Fixed year effect	be	be	be	Fixed year effect	be	be	be
Cons	−2.605 ***	−0.537 ***	−1.720 ***	Cons	−2.605 ***	−0.407 ***	−1.978 ***
	(−7.66)	(−6.41)	(−5.49)		(−7.66)	(−4.89)	(−6.25)
N	2602	2602	2602	N	2602	2602	2602
R^2	0.248	0.167	0.372	R^2	0.248	0.162	0.355

Note: ** means $p < 0.05$, *** means $p < 0.01$

5. Conclusions and Recommendations

This study employs panel data from energy enterprises listed on the Shanghai and Shenzhen A-share markets between 2007 and 2022. Utilizing fixed-effects models and bootstrap decomposition methods, it constructs three models: a mediation effect model examining the relationship between digitalization, green innovation, and the green transformation of energy enterprises; a moderation effect model analyzing the interaction among digitalization, environmental regulations, carbon intensity, and green transformation; and a mixed model investigating the combined effects of digitalization, environmental regulations, and carbon intensity on green innovation within energy enterprises. Through these models, the study examines the mediating mechanism of green innovation in the process of digitalization influencing energy companies' green transformation, the moderating effect mechanism of environmental regulations and carbon intensity on digitalization's impact on green transformation, and explores the joint influence of environmental regulations and carbon intensity on green innovation when synergizing with digitalization and green innovation, respectively. Furthermore, this study categorizes research samples based on regional attributes, ownership attributes, scale attributes, and energy attributes to analyze the heterogeneity of the mediating effect mechanism across different types of energy enterprises. Findings reveal that digitalization and green innovation exert a significant, positive, partial mediating effect on the green transformation of energy enterprises. This mediating effect is notably stronger in central and western regions, non-state-owned enterprises, and large-scale, low-pollution energy enterprises compared to those in eastern regions, state-owned enterprises, and small-to-medium-sized, high-pollution energy enterprises.

Increased carbon intensity in energy enterprises enhances the promotional effect of digitalization on their green transformation, whereas environmental regulations weaken this effect. Environmental Regulation 1 exhibits no significant promotional or inhibitory effect when synergizing with digitalization in green innovation, whereas Environmental Regulation 2 shows a significant inhibitory effect, with carbon intensity exerting a significant promotional effect. Based on these empirical findings, the following recommendations are proposed.

First, develop intelligent energy systems and refine energy management processes. Digital technologies enable energy companies to build smart energy systems. By integrating renewable and traditional energy sources, companies can achieve intelligent management of energy production, transmission, and consumption. For example, building smart grids and developing energy internet platforms can effectively improve the efficiency and stability of energy systems, reduce energy waste, and lower carbon emissions. By leveraging technologies such as big data and artificial intelligence, companies can develop intelligent energy management systems to monitor and optimize energy usage in real-time. Through data analysis and prediction, companies can identify areas of energy waste, optimize production processes, and improve equipment operational efficiency, thereby reducing energy consumption and operational costs.

Second, improve energy efficiency and strengthen green innovation. Digital technologies can help companies develop and implement energy-saving solutions, as well as promote the adoption of clean energy. By optimizing resource allocation and production processes, companies can significantly enhance energy efficiency, reduce pollutant emissions, and facilitate a green transformation. Green innovation plays a crucial intermediary role in the digital transformation and green transition of energy companies. Businesses should increase their investment in green innovation to drive the research, development, and application of green technologies. Through green innovation, businesses can not only enhance their market competitiveness but also contribute to the sustainable development of the industry.

Third, strengthen policy support and collaborative cooperation, and implement regional differentiation strategies. Develop policy measures to promote the coordinated development of traditional and new energy sources, and encourage complementary cooperation between the two in areas such as energy supply, energy storage, and peak load regulation. The government should provide increased policy support for the green transformation of energy companies, offering financial, technological, and policy guarantees. At the same time, energy companies should collaborate with upstream and downstream enterprises in the industrial chain, research institutions, and government agencies to jointly promote technological innovation, business model innovation, and policy innovation in the energy sector, thereby building an open, shared, and collaborative green intelligent energy ecosystem. Given the significant differences in economic development levels and resource endowments across regions in China, energy companies should adopt differentiated strategies to advance their green transformation. Eastern regions should fully leverage the advantages of digital technology to drive the rapid development of green innovation. Central regions should focus on the conversion and application of green innovation outcomes. Western regions should strengthen infrastructure construction to enhance the foundational capabilities for green innovation.

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