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China's Digital Economy: A Dual Mission of Carbon-Emission Reduction and Efficiency Enhancement

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Abstract: With the introduction of China's dual carbon goals and the rise of the digital economy as a new model of economic development, the role of the digital economy in achieving green growth is garnering increasing attention. This paper constructs a comprehensive digital economy index, utilizing panel data from 30 provinces in China between 2006 and 2017, and employs the System GMM method to examine the comprehensive impact of the digital economy on low-carbon development from the perspectives of "emission reduction" and "efficiency enhancement". The primary findings indicate that the digital economy aids China in meeting its dual carbon goals by reducing carbon emissions (CEs) and increasing carbon emissions' efficiency (CEE). However, this impact varies with different components of the digital economy, and the role of digital finance is limited. This conclusion underscores the necessity of subdividing digital economy indicators. Our conclusions have been substantiated through various robustness checks, including but not limited to the method of distinguishing pure emission reduction from efficiency enhancement. Additionally, our research reveals the dynamic nonlinear effects of the digital economy in promoting emission reduction and efficiency enhancement. Green regulations that exceed a threshold value enhance emission reduction and efficiency, while the impact of sustainable technological innovation may be constrained by changes in policy and market environments. Academically, this study offers a new perspective on the complex relationship between the digital economy and its effectiveness in reducing carbon and enhancing efficiency. From a policy standpoint, it provides insights for China and other countries in advancing energy conservation and emission-reduction initiatives.



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Keywords: digital economy; carbon emissions efficiency; carbon emissions; system GMM; dynamic threshold model

1. Introduction

With the increasing urgency of global climate change challenges, low-carbon development strategies have become key to addressing the greenhouse effect worldwide [1–3]. Particularly in China, since the 2009 Copenhagen Climate Change Conference, the government has actively committed to reducing carbon emissions, aiming to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [4,5]. This is not only an intrinsic requirement for China's sustainable development but is also a proactive response to global climate responsibilities. However, the transition from policy to practice involves navigating through multiple challenges including technological, economic, and societal barriers, highlighting the pressing issue of how to effectively advance low-carbon transformation and enhance carbon-emission efficiency.

Meanwhile, the digital economy, as an innovative economic development model, provides a new perspective for sustainable development strategies [6,7]. According to the "2022–2027 China Digital Economy Market Demand Forecast and Development Trend Outlook Report" released by the China Business Industry Research Institute, the market

size of China's digital economy reached CNY 50.2 trillion in 2022, accounting for 41.5% of the GDP. The report also predicts that the market size will increase to CNY 63.8 trillion by 2024. These figures indicate that the digital economy has become a key driver in China's economic transformation and sustainable development [8]. In contrast, previous research has mainly focused on the drivers and constraints of low-carbon development under traditional economic conditions, such as economic growth [9,10], industrial structure [11–13], energy structure [14,15], technological progress [16,17], and environmental regulation [18].

Currently, the academic community has not yet reached a consensus on the complex relationship between digital economy and carbon-emission efficiency (CEE), the transformation of resource utilization patterns, and the association of digital economy with carbon emissions (CEs) [19–21]. Studies by Ma et al. [22] and Li et al. [23] suggest that the digital economy, by optimizing energy structures, increasing R&D investments, and promoting technological innovation, effectively reduces CE, thereby fostering the development of China's low-carbon economy. Particularly, digital economic platforms centered around big data and cloud computing contribute to reducing energy consumption per unit of carbon emissions by enhancing the efficiency of resource allocation [24]. This view is supported by the research of Zhang et al. [25] and Chen et al. [26], which indicates a significant impact of digital economy development on improving energy efficiency. However, Raheem et al. [27] point out potential adverse side effects in the process of promoting emission reduction due to digital development. This study primarily analyzes the high energy-consumption challenges faced during the establishment of digital economic infrastructure and highlights limitations in the adoption of innovations within the digital economy. These issues could limit the potential of the digital economy in reducing emissions [28–30].

Current research exhibits significant limitations, particularly in understanding the depth and breadth of the complex interaction between the digital economy and sustainable development. In reality, achieving peak carbon emissions and carbon neutrality are two phases of the same goal. Actively promoting the low-carbon transition driven by the digital economy requires simultaneous consideration of both reducing CEs and enhancing CEE. Moreover, current studies mainly focus on exploring the impact of digital economy development on CEs through mediating effects [22,31], or investigating the spatial effects and regional heterogeneity of CEs [21,32,33]. However, simultaneously examining carbon emission's dynamic changes and potential nonlinear effects from both perspectives has not yet received sufficient attention.

Examining global trends, countries typically encounter a stabilization phase in carbon emissions after reaching a peak. This plateau's characteristics and duration vary, underscoring the complexities of transitioning to lower emissions. Despite the potential of emission-reduction technologies like carbon capture and negative emissions, their practical application faces uncertainties and challenges, including technological, economic, and societal barriers [34]. Our study investigates the digital economy's capability to enhance both the "quality" of emission reductions—ensuring their effectiveness and sustainability—and their "quantity" or scale. This investigation is crucial for assessing the digital economy's role in expediting China's progress towards a carbon peak and fostering a low-carbon economy transition. Addressing these questions, we consider not only the development of digitalization itself but also incorporate green regulations and sustainable technological innovation into our research. In essence, the strengthening of environmental regulations may increase operational costs for businesses [35], affecting their motivation to reduce emissions, while the advancement of sustainable technological innovation might enhance the technical capability and efficiency of businesses in emission reduction [36,37].

To address these issues, our study makes marginal contributions in the following aspects. Firstly, our study approaches the analysis of the digital economy's impact on emission reduction and efficiency enhancement from two dimensions: the quantity and efficiency of carbon emissions. We incorporate these aspects into our framework and further eliminate any overlapping effects between these two paths to accurately assess the true "emission reduction" and "efficiency enhancement" effects. This approach en-

riches the current theories related to digital development and sustainable development. Secondly, we delve further into the specific impact of four core components of the digital economy on China's low-carbon development. We recognize that the digital development indicators of economies are multidimensional and complex concepts, and a single indicator is insufficient to fully measure their level of development. The analysis results indicate that China's digital finance has produced unexpected environmental side effects. Lastly, employing a dynamic threshold model, our study discovers that with the strengthening of green regulations and innovation in sustainable technologies, the impact of the digital economy on reducing carbon emissions and enhancing efficiency exhibits significant dynamic nonlinearity. This finding is crucial for formulating effective environmental policies and promoting innovation in clean technologies. The practical value of our research lies in providing insights for policymakers on how to leverage digital development to foster green growth, emphasizing the need to consider green regulation and technological innovation in tandem while advancing the digital economy, to maximize its role in low-carbon transformation.

The structure of our study is as follows: Section 2 proposes research hypotheses through a review of the existing literature; Section 3 introduces the research methods and data used; Section 4 discusses the empirical results; Section 5 provides further discussion; and finally, the study concludes with a summary of findings and policy recommendations.

2. Literature Review and Hypotheses

In this study, we adopt the conceptualization of the digital economy as initially proposed by Tapscott [38], which characterizes it as a novel economic system founded on digital technologies and networks. This definition has evolved alongside rapid advancements in information technology, positioning the digital economy as a central force in global societal progress and economic development. The digital economy's role in driving technological advancement, enhancing the efficiency of factor use, and facilitating industrial restructuring is pivotal. These elements are instrumental in promoting both emission reductions and efficiency improvements within the context of low-carbon development.

2.1. The Influence of Digital Economic Growth on CE

On the supply side, the digital economy, supported by advanced information technology, plays a significant role in enhancing the efficiency of resource and energy use, leading to smarter and more flexible production methods [39–41]. This transformation not only redefines the creation process of products and services but also enables enterprises to gain competitive advantages in the digital environment [42]. It reduces the costs of searching, categorizing, and analyzing carbon information, facilitating the establishment of a standardized CE system [43]. Moreover, digital carbon-pricing mechanisms enhance the transaction efficiency and scale of the carbon-emission market, mitigating CEs' negative externalities [44,45]. However, we acknowledge the potential uneven distribution of these benefits, which could exacerbate the digital divide if certain groups or regions lack access to advanced technologies. The production and use of digital technologies themselves contribute to energy consumption and carbon footprints, potentially offsetting the positive effects of digitalization on resource efficiency [46]. Moreover, challenges related to e-waste, data security, and privacy concerns within the digital economy necessitate a balanced approach, integrating technological solutions with systemic changes and policy measures to ensure sustainable development [47]. On the demand side, while digital products and services offer eco-friendly alternatives, the substantial electricity consumption of the digital industry underscores the importance of considering the net impact of the digital economy on CEs comprehensively [48]. Lastly, While the digital industry, which heavily relies on electricity, can lead to substantial electricity consumption and carbon emissions, the overall impact of the digital economy on carbon emissions is a net decrease when considering both digital and non-digital industries [46]. Overall, leveraging the digital economy's potential for energy efficiency improvements and industrial transformation can significantly con-

tribute to lowering carbon emissions and promoting sustainable development. This leads us to formulate Hypothesis 1.

Hypothesis 1. *The advancement of the digital economy contributes to lowering quantity of CEs.*

2.2. Analyzing the Digital Economy's Role in Enhancing CEE

The digital economy, through its integration of advanced technologies and digital-intensive industries, fundamentally transforms economic development towards enhancing environmental sustainability alongside growth [49]. This transformation is primarily realized by improving output efficiency, which directly influences CEE. Efficiency enhancement in this realm is achieved by leveraging technological innovation, including big data and cloud computing, which optimizes production processes and fosters effective industry collaboration. This reduces unnecessary resource consumption and boosts production efficiency [50,51]. Furthermore, data, as novel primary production factors, substitute traditional resources, facilitating the development of low-carbon digital products and services [52], which in turn contribute to carbon-emission reduction. The digital economy also encourages energy conservation and efficiency across various sectors by applying digital technologies that optimize energy use [53]. Moreover, it enhances market transparency in energy supply and demand, enabling more coordinated energy scheduling and utilization [54], which ensures the most rational allocation of energy resources. Additionally, it supports the principles of a circular economy, minimizing waste and maximizing product value [55], thereby contributing to carbon efficiency.

Through these mechanisms, the digital economy not only acts as a catalyst for enhancing carbon efficiency but also signifies a shift towards sustainable production and consumption patterns. This underscores the proposition that the development of the digital economy significantly enhances CEE, marking a pivotal contribution to environmental sustainability without compromising economic growth. Therefore, we propose Hypothesis 2.

Hypothesis 2. *The development of the digital economy enhances CEE.*

2.3. The Dynamic Nonlinear Impact of the Digital Economy on Low-Carbon Development

Green environmental regulation serves as a foundational strategy for regions to confront climate change and foster green development, playing a pivotal role in realizing dual carbon objectives [56]. In this context, the interaction between green regulation and the digital economy's contribution to low-carbon development is of paramount importance. While existing studies have highlighted that stringent green regulations can effectively reduce CEs and lower the total carbon output of businesses [57,58], they also suggest a complex relationship influenced by increased operational costs for enterprises. This complexity hints at a potential nonlinear impact on low-carbon development, necessitating a deeper exploration. The digital economy, with its inherent efficiency and innovation, intersects with green regulation in ways that could both amplify and moderate its impact on emission reduction and efficiency enhancement [59]. Specifically, at initial stages of regulatory stringency, the costs associated with compliance and technological upgrades may outweigh the immediate benefits in terms of emission reduction and efficiency gains [60]. However, beyond a certain threshold of regulatory pressure and technological adaptation, the digital economy could leverage green regulations as a catalyst for breakthrough innovations in low-carbon technologies and processes [59]. This scenario posits a nonlinear relationship where the impact of green regulation on low-carbon development initially presents challenges but eventually transitions to significant benefits as digital economy integration deepens.

This nonlinear dynamic can be attributed to several factors. First, the initial cost of adapting to green regulations may deter short-term investments in digital low-carbon innovations. Over time, however, as companies adapt and innovate, the marginal costs de-

crease while the benefits of compliance and efficiency gains increase exponentially. Second, the digital economy enables more sophisticated data analytics and automation technologies [61], which can transform regulatory compliance from a burden into a competitive advantage, further driving down emissions and enhancing efficiency in a nonlinear fashion. Therefore, we propose Hypothesis 3. This hypothesis anticipates a transformational impact of green regulation, mediated by the digital economy, which evolves from an initial phase of adaptation challenges to a subsequent stage of substantial low-carbon advancements.

Hypothesis 3. *Under green regulation, the development of the digital economy exhibits a dynamic nonlinear relationship with emission reduction and efficiency enhancement in the low-carbon development process.*

Sustainable technological innovation stands at the forefront of driving sustainable development and serves as a crucial mechanism for reducing CEs and improving CEE [62]. The proliferation of the internet and its innovative applications have ushered in a new era of energy conservation and pollution reduction [63], underscoring the transformative impact of digital technologies on environmental sustainability. The integration of green technological innovations within production processes catalyzes the shift towards green production methodologies and the adoption of clean energy sources, thereby mitigating CE during production. Furthermore, it encourages low-carbon consumption patterns, extending the benefits of reduced CEs into the daily lives of consumers.

Tang et al. [64] highlight the role of digital infrastructure in enhancing informatization levels, which in turn boosts media coverage and corporate governance, fostering an environment conducive to green technological innovation. Xu et al. [65] emphasize the critical importance of green technological innovation in elevating CEE. By optimizing the efficiency of factor utilization and product supply, green technological innovation generates more economic value from fewer resources. This process not only drives industrial modernization but also amplifies energy efficiency, collectively facilitating significant improvements in CEE.

Building on this foundation, the relationship between sustainable technological innovation and the digital economy is characterized by a symbiotic dynamic where each element reinforces the other. Sustainable technological innovations provide the tools and methodologies necessary for the digital economy to reduce emissions and enhance efficiency [66,67]. In return, the digital economy amplifies the reach and effectiveness of these innovations, creating a feedback loop that accelerates progress towards emission reduction and efficiency enhancement.

Thus, we present Hypothesis 4. This hypothesis posits that the confluence of sustainable technological innovation and digital economic growth creates a fertile ground for achieving substantial environmental gains, marking a decisive step towards realizing the dual goals of economic prosperity and environmental sustainability.

Hypothesis 4. *Under the umbrella of sustainable technological innovation, the digital economy plays a pivotal role in further advancing emission reduction and efficiency enhancement.*

3. Methodology and Data

3.1. Methodology

3.1.1. Benchmark Model

Considering the influence of potential factors, in our STIRPAT (stochastic regression on population, affluence, and technology model), P is replaced by urbanization rate [68]; A is replaced by per capita GDP and energy consumption [69]; and T is represented by foreign direct investment and research and development intensity [70]. Given that the Environmental Kuznets Curve (EKC) hypothesis suggests an inverted U-shaped relationship between economic development and environmental quality [71], we introduce the squared term of per capita GDP into our model. In the current macroeconomic environment where

sustainable development is deeply integrated with the real economy, research confirms that sustainable development significantly impacts carbon emissions [72]. Therefore, including dig_{it} as a driving factor for low-carbon development in our theoretical model aligns with the current macroeconomic context. The extended STIRPAT model is set as Equation (1):

$$Y_{it} = f(dig_{it}, pgdp_{it}, pgdp_{it}^2, energy_{it}, fdi_{it}, Url_{it}, RD_{it}) \quad (1)$$

Here, Y is the dependent variable representing CEs and CEE, dig represents the level of digital economy development, $pgdp$ represents the regional per capita economic development level, $energy$ represents energy consumption, fdi represents the level of foreign direct investment, url represents urbanization rate, and RD represents research and development investment intensity.

Considering the persistence among economic factors, where outcomes of one period can influence the subsequent period, implementing a dynamic adjustment mechanism becomes crucial [73,74]. To accommodate this, we incorporate a lagged variable of low-carbon development into the equation, leading to the formulation of a dynamic panel regression model. This method is more effective in addressing potential endogeneity issues and improves the accuracy of model estimation. The dynamic panel regression model is as follows:

$$\ln Y_{it} = \beta_0 + \beta_1 \ln Y_{it-1} + \beta_2 \ln dig_{it} + \sum_{k=1}^6 \beta_k \ln X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

In Equation (2), X_{it} represents a series of control variables. μ_i and γ_t are the fixed effects for province and time, respectively. ε_{it} represents the random error term. β_0 represents the intercept, and $\beta_1 - \beta_k$ are the coefficients to be estimated.

3.1.2. Dynamic Threshold Panel Model

Considering China's vast territory and uneven economic development, relying solely on traditional static threshold models to capture the nonlinear relationships between variables may lead to biases and endogeneity issues due to limitations in data processing and model-estimation methods. This challenge highlights the necessity of employing more advanced models and analytical approaches to more accurately analyze and interpret the complex interactions between the digital economy and environmental variables across different regions and economic contexts in China. Therefore, this study, drawing on the approach of [75], and considering green regulation and sustainable technological innovation as threshold variables, constructs a dynamic threshold regression model.

$$\begin{aligned} \ln Y_{it} = & \beta_0 + \beta_1 \ln Y_{it-1} + \beta_2 \ln dig_{it} \cdot I(qit \leq \theta) + \beta_3 \ln dig_{it} \cdot I(qit > \theta) \\ & + \sum_{k=1}^6 \varphi_k \ln X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \end{aligned} \quad (3)$$

where Y_{it-1} represents the lagged term of CEs and CEE; qit is the threshold variable; $I(\bullet)$ is an indicator function, equal to 1 when the condition in the brackets is satisfied, otherwise 0; θ is the threshold value; other parameters are set as above.

3.2. Data

3.2.1. Dependent Variable

In this study, we selected CEs and CEE as the dependent variables to explore the pathways to achieving the dual carbon goals from the perspectives of "emission reduction" and "efficiency enhancement". From the perspective of "emission reduction", we focus on the reduction of CEs, indicating that a region is progressing towards low-carbon development. We use the CEs of each province in China as the indicator for "emission reduction" and have transformed it into natural logarithms. Since direct CE data is not provided by

the provinces in China, this study calculates provincial CEs based on the methodology provided by the Intergovernmental Panel on Climate Change (IPCC).

From the perspective of “efficiency enhancement”, we observe that the relationship between economic growth and greenhouse gas emissions is gradually decoupling, that is, achieving lower CEs during the process of economic development [9]. In our study, we use the Data Envelopment Analysis model to assess the efficiency of carbon emissions as a key metric for measuring efficiency improvement. The input variables of the model include capital (K), labor (L), and energy (E), with the desired output being GDP (Y) and the undesired output being carbon emissions (C). Although the DEA method has advantages in measuring the efficiency of negative outputs, it also faces potential issues with linear programming models and measurement biases due to slack in input and output variables. Therefore, we adopted a non-oriented, non-radial Directional Distance Function approach, combining the study on environmentally bad outputs by Zhou et al. [76] and the comprehensive technology proposed by Afsharian and Ahn [77], to construct a more precise DEA model for assessing the CEE of Chinese provinces.

3.2.2. Independent Variable

The digital economy, with its intricate web of influences across various dimensions, necessitates a multifaceted assessment to unravel its potential impact on achieving dual carbon goals. Although many studies tend to use a single indicator or assess the development of the digital economy from only one perspective [78–80], such approaches might not fully reveal the multifaceted nature of the digital economy. Recognizing the limitations of narrow, single-indicator analyses that fail to capture the digital economy’s comprehensive nature, our study adopts a broad-based index, comprising 21 indicators (Table 1). These indicators span digital infrastructure, inclusive finance, innovation capability, application scope, economic growth, and the professional internet workforce. This selection is grounded in the literature’s recommendations [39,81] and mirrors the trajectories of China’s digital economy’s evolution.

To elucidate our choice of indicators, we delve into the rationale behind each category:

- Digital Infrastructure: essential for underpinning the digital economy’s expansion, facilitating energy-efficient technologies and services;
- Inclusive Finance: reflects the digital economy’s reach, including access to green finance solutions that support low-carbon projects;
- Innovation Capability and Application Scope: measures the digital economy’s role in fostering green technologies and practices;
- Economic Growth and Internet Professionals: indicates the digital economy’s scale and the talent driving sustainable digital solutions.

3.2.3. Other Variables

To elucidate the mechanisms by which the digital economy impacts low-carbon development, this study employs green regulation (gr) and sustainable technological innovation (sti) as threshold variables to examine the digital economy’s nonlinear effects on low-carbon development (see Appendix A for a detailed introduction of threshold variables). Furthermore, acknowledging that low-carbon development is influenced by a complex interplay of multiple factors, our research incorporates additional control variables to reveal the comprehensive impact of multidimensional factors on low-carbon development. These include economic growth (pgdp), to capture the general economic conditions that might affect both digital economy growth and carbon emissions; energy consumption scale (energy), as a direct factor influencing carbon emissions [82]; foreign direct investment (fdi), which can bring advanced technologies and practices conducive to low-carbon development; urbanization level (urb), reflecting changes in lifestyle and energy-consumption patterns with urban development [83]; and science and technology research and development intensity (RD), indicating the capacity for innovation and sustainable development. To test the Environmental Kuznets Curve (EKC) hypothesis, we further incorporate the squared term

of economic growth (pgdp2), suggesting a nonlinear relationship between economic development and environmental quality. Specific descriptions of these variables are presented in Table 2.

Table 1. Assessment framework for the overall progress of China’s digital economy.

First-Grade Index	Second-Grade Index	Unit	Data Source
Digital infrastructure (difa)	CN web identifiers	10 thousand Pcs	National Bureau of Statistics
	Total count of web portals	10 thousand Pcs	
	Percentage of IPv4 allocations	%	
	Mean data size per webpage	10 thousand Pcs	
	Quantity of broadband connectivity gateways	10 thousand Pcs	
Digital inclusive finance index (difi)	The capacity of mobile communication switches	10 thousand Pcs	China Electronic Information Industry Statistical Yearbook
	Extent of transcontinental fiber-optic strands	10 thousand Km	
	Aggregate count of cellular-device subscribers	10 thousand Pcs	
	The total number of broadband internet users	10 thousand Pcs	
	Web access-diffusion rate	%	
Digital innovation capability and application degree (diad)	Percentage of staff with tertiary education in IT services	%	China Statistical Year book on Science and Technology
	Investment in scientific and technological sectors	CNY 100 million	
	Ratio of research personnel in IT sectors	%	
	Count of tech-economy patents per capita	pcs	
	Adoption rate of advanced digital solutions in public corporations	%	
Economic growth and number of internet workers in the field (egiw)	Tally of firms in electronic data production	Pcs	National Bureau of Statistics
	Capital holdings in electronic data manufacturing	CNY 100 million	
	Workforce size in IT and software services	Pcs	
	Pay scales in IT and software sectors	CNY	
	Trade volume of digital information goods	CNY 100 million	
	Mean workforce count in the digital manufacturing sector	Pcs	

Table 2. Control variables.

Variables	Symbol	Unit	Measurement Methods
Economic growth	pgdp	CNY 100 million	Per GDP.
The squared term of economic growth	pgdp2	-	-
Total energy consumption	energy	10,000 tce	The total energy consumption.
Foreign direct investment	fdi	USD 1000	The international investment utilized by each province.
Urbanization	urb	%	It is quantified by calculating the proportion of the population with urban registration compared to the total registered population in the city at the year’s end
R&D investment	RD	%	The percentage of R&D investment to its provincial GDP.
Green regulations	gr	10,000 tons	It is evaluated based on metrics such as the treatment of industrial wastewater, emissions of industrial sulfur dioxide, and particulate matter, alongside the economic output from industrial sectors
Sustainable technological innovation	Sti	Unit	It is gauged by the total count of granted green patent approvals.

3.2.4. Data Sources

In this research, we analyze panel data spanning from 2006 to 2017, covering 30 Chinese provinces. The data are primarily derived from the National Bureau of Statistics of China, alongside the Electronic Information Industry Statistical Yearbook, and the China Statistical Yearbook on Science and Technology. Additionally, data on green innovation were sourced from the China Research Data Services (CNRDS). To ensure accuracy and consistency, foreign direct investments denominated in US dollars were converted to Renminbi using the exchange rates of the respective years, and all value-added data were deflated to 2006 prices. Descriptive statistics for each variable can be found in Table 3. It is observable that some provinces have made significant progress in improving energy efficiency and reducing carbon intensity, while others have progressed more slowly. In terms of promoting sustainable technological innovation, some provinces are more proactive, whereas others lag behind. Such disparities may be influenced by a variety of factors, including economic resources, technological foundations, policy support, and industrial structures. Addition-

ally, the level of digital economy development also demonstrates significant differences among provinces.

Table 3. Statistical description.

Variable	N	Mean	SD	Min	Max
ce	360	5.420	0.752	2.955	6.736
cee	360	6.030	1.036	3.840	7.484
dig	360	−2.806	0.997	−5.580	−0.185
pgdp	360	1.624	0.342	0.804	2.519
pgdp2	360	2.754	1.133	0.647	6.348
energy	360	9.288	0.696	6.814	10.57
fdi	360	10.73	1.406	7.601	14.38
urb	360	−0.656	0.245	−1.293	−0.088
RD	360	0.203	0.163	0.005	0.880
gr	360	0.523	0.527	0	2.585
sti	360	5.082	1.545	0	9.116

4. Empirical Results and Discussion

4.1. Results

To explore whether the development of the digital economy effectively controls CEs and improves CEE, this paper employs a two-way fixed effects static panel model, as well as two dynamic panel models: the System Generalized Method of Moments (SYS-GMM) and the Difference Generalized Method of Moments (D-GMM). Compared to Difference GMM, System GMM more effectively corrects for potential endogeneity issues [84,85]. Therefore, the focus of this paper is on the estimation results of the System GMM, while also providing comparative analyses of other estimation methods. The estimation results are presented in Table 4.

Table 4. Estimation results—linear model.

Variable	FE		SYS-GMM		D-GMM		Bootstrap 1000 Times	
	(1) ce	(2) cee	(3) ce	(4) cee	(5) ce	(6) cee	(7) ce	(8) cee
L.ce			0.364 *** (9.725)		0.253 *** (5.542)			
L.cee				1.009 *** (283.397)		0.463 *** (12.520)		
dig	−0.049 * (−1.790)	0.026 ** (2.365)	−0.071 *** (−6.794)	0.042 *** (8.037)	−0.048 *** (−7.230)	0.010 *** (2.900)	−0.194 *** (−7.274)	0.329 *** (3.459)
pgdp	0.437 *** (3.351)	0.088 * (1.684)	0.539 *** (3.622)	−0.136 *** (−8.536)	0.778 *** (5.319)	−0.120 *** (−5.670)	0.302 (1.505)	0.076 (0.099)
pgdp2	−0.119 *** (−3.184)	0.028 * (1.867)	−0.149 *** (−3.165)	0.027 *** (4.872)	−0.220 *** (−5.494)	0.063 *** (9.597)	−0.069 (−1.121)	−0.381 * (−1.650)
energy	1.070 *** (24.738)	−0.134 *** (−7.724)	0.772 *** (19.455)	−0.044 *** (−9.046)	0.806 *** (14.134)	−0.085 *** (−13.665)	1.158 *** (63.202)	0.707 *** (11.736)
fdi	−0.014 (−1.017)	0.023 *** (4.018)	0.027 *** (3.592)	0.006 *** (3.354)	0.024 *** (2.838)	0.007 *** (6.278)	0.061 *** (3.774)	0.319 *** (5.420)
urb	0.139 (1.328)	−0.043 (−1.032)	−0.255 *** (−3.728)	0.037 ** (2.456)	−0.237 ** (−2.075)	0.163 *** (10.711)	0.041 (0.687)	−1.808 *** (−7.426)
RD	−0.195 (−1.341)	−0.021 (−0.360)	−0.264 *** (−3.178)	−0.120 *** (−6.838)	−0.101 * (−1.690)	−0.090 *** (−3.474)	−0.254 *** (−3.144)	−1.274 *** (−4.816)
cons	−4.758 *** (−10.094)	6.859 *** (36.333)	−4.770 *** (−14.359)	0.607 *** (10.028)	−4.609 *** (−9.543)	4.142 *** (18.184)	−6.759 *** (−16.210)	−3.040 ** (−2.091)
N	360	360	330	330	300	300	360	360
R ²	0.995	0.990					0.956	0.681
F	115.787	16.876						
AR(1)			0.0132	0.0031	0.0100	0.0103		
AR(2)			0.6826	0.3327	0.6652	0.4166		
Sargantest			0.8050	0.5008	0.2474	0.0625		

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; t -statistics in parentheses.

The System GMM estimation results reveal the significant impact of the digital development on CE and CEE. By considering the dynamism of carbon emissions and efficiency—represented by the lagged terms $L.ce$ and $L.cee$ —it is found that the growth of the digital development significantly reduces CE and improves CEE. This outcome highlights the dual role of digital development in driving the low-carbon transition of Chinese provinces: reducing emissions and enhancing emission efficiency. The impact of digital economic growth on CEs and CEE is primarily realized through enhancing the efficiency of production and operations as well as promoting more optimized use of energy and resources. Firstly, by integrating advanced information technologies such as big data and cloud computing, the digital economy optimizes production processes, reduces unnecessary resource consumption, and improves industrial collaboration efficiency, thereby directly lowering CEs. Secondly, digitalization enhances energy utilization efficiency by facilitating more transparent and coordinated energy scheduling and usage, supporting the improvement of carbon emission efficiency. These insights are crucial for understanding how the digital economy contributes to sustainable development.

The autocorrelation test (Arellano–Bond test) results show $AR(1) < 0.1$, $AR(2) > 0.1$, indicating no first-order autocorrelation in the model. The Sargan test's p -value being greater than 0.1 validates the effectiveness of the instrumental variables used. To improve the robustness of the regression results, this study was tested by 1000 times bootstrapping regression. Therefore, Hypotheses 1 and 2 of this study are supported.

Regarding control variables, the coefficient of the first term of $pgdp$ is significantly positive, while the coefficient of the second term is significantly negative, indicating an inverted U-shaped relationship. This is consistent with the findings of Sun et al. [86], suggesting that China's economic growth has an increasing and then decreasing impact on CEs. The influence on CEE presents a U-shaped relationship, implying lower CEE in the early stages of economic development due to environmental neglect, which significantly improves with further economic development and the application of clean technologies. Energy consumption significantly increases CEs, highlighting the need for improved energy efficiency and clean-energy use [82]. Conversely, it lowers CEE, urging the optimization of energy use. Foreign direct investment positively affects both carbon emissions and their efficiency, suggesting it brings both challenges and advanced technologies that enhance efficiency. Urbanization reduces emissions, attributed to better energy use and clean-technology adoption, while also improving carbon efficiency, indicating efficient urban energy management. Research and development (R&D) investment cuts CEs by encouraging new, efficient technologies and positively affects carbon efficiency, aiding the shift towards low-carbon development.

In summary, the analysis of these variables emphasizes the significance of optimizing energy consumption patterns, carefully considering the quality of foreign direct investments, promoting green development in the urbanization process, and increasing investments in research and development for advancing low-carbon development and enhancing carbon-emission efficiency. Moving forward, we will primarily address issues of endogeneity and the robustness of the results to ensure the accuracy of our empirical findings.

4.2. Robustness Check

4.2.1. A New Dependent Variable

To verify the robustness of the baseline-regression model's estimations, this study adopts a strategy of changing the dependent variables. Specifically, per capita carbon emissions (pce) are used to measure the reduction effect, and a new carbon emission efficiency index ($cee1$) is estimated based on the DEA model to measure the efficiency enhancement effect. The estimation results are shown in columns (1) and (2) of Table 5. These results indicate that, even after changing the dependent variables, the significant impact of the digital economy on regional CE and CEE is maintained, thereby strengthening the robustness of the baseline-regression results.

Table 5. Results of robustness check.

Variables	Replacement of Dependent Variables		Replacement of Core Independent Variables		Reduced Sample Interval		Exclusion of Central Government Municipalities	
	(1) pce	(2) cee1	(3) ce	(4) cee	(5) ce	(6) cee	(7) ce	(8) cee
L.pce	0.717 *** (11.780)							
L.cee1		1.042 *** (99.341)						
L.ce			0.342 *** (8.022)		0.507 *** (9.791)		0.329 *** (7.847)	
L.cee				1.009 *** (310.332)		1.009 *** (233.692)		1.016 *** (246.214)
dig	−0.172 *** (−15.000)	0.031 ** (2.270)			−0.096 *** (−5.426)	0.035 *** (7.918)	−0.082 *** (−10.265)	0.034 *** (8.231)
digf			−0.035 *** (−5.391)	0.026 *** (9.144)				
pgdp	0.480 * (1.954)	−0.433 *** (−3.702)	0.693 *** (4.769)	−0.195 *** (−5.208)	0.322 *** (2.874)	−0.150 *** (−6.670)	0.673 *** (3.457)	−0.177 *** (−4.728)
pgdp2	−0.122 * (−1.766)	0.186 *** (6.472)	−0.204 *** (−4.396)	0.049 *** (4.663)	−0.104 *** (−3.479)	0.036 *** (5.281)	−0.176 *** (−2.849)	0.047 *** (3.974)
energy	0.343 *** (11.931)	−0.115 *** (−8.049)	0.775 *** (18.286)	−0.040 *** (−3.473)	0.726 *** (19.876)	−0.041 *** (−7.111)	0.745 *** (18.739)	−0.040 *** (−3.976)
fdi	−0.003 (−0.180)	−0.034 *** (−2.656)	0.025 *** (3.470)	0.005 *** (2.580)	0.009 (1.153)	0.009 *** (5.140)	0.010 (1.487)	0.004 (1.361)
urb	0.205 * (1.687)	−0.050 (−0.390)	−0.275 *** (−3.527)	0.054 *** (2.854)	−0.184 *** (−2.782)	0.036 * (1.932)	−0.176 ** (−2.299)	0.037 * (1.845)
RD	−0.159 (−0.760)	−0.046 (−0.607)	−0.233 (−1.407)	−0.117 *** (−4.916)	−0.198 ** (−2.494)	−0.129 *** (−7.462)	0.031 (0.169)	−0.187 *** (−7.518)
_cons	−3.373 *** (−11.381)	1.452 *** (3.748)	−4.630 *** (−14.337)	0.563 *** (6.710)	−4.728 *** (−13.671)	0.541 *** (7.961)	−4.323 *** (−14.284)	0.558 *** (7.195)
N	330	330	330	330	330	330	286	286
AR(1)	0.0064	0.0265	0.0127	0.0025	0.0047	0.0016	0.0199	0.0066
AR(2)	0.4307	0.5930	0.6751	0.3715	0.3392	0.2865	0.7404	0.4913
Sargan test	0.8490	0.5352	0.8412	0.4677	0.6172	0.4138	0.9174	0.7250

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; t -statistics in parentheses.

4.2.2. A New Explanatory Variable

This study, referencing [87,88], re-measures the comprehensive index of the digital economy in Chinese provinces using the fully arranged polygon graphical index method. The advantage of this method is that it does not rely on expert evaluation in the calculation process, effectively reducing errors caused by subjective judgments. The regression results are consistent with expectations.

4.2.3. Reduced Sample Interval

To eliminate potential biases due to the sample time selection, this study excludes data from 2006 and 2017, using only panel data from 2007 to 2016 for re-estimation. According to the regression results in columns (5) and (6) of Table 5, even with a reduced sample time span, the sign of the coefficients of the main explanatory variables remains consistent with the baseline-regression results, demonstrating the time robustness of the analysis.

4.2.4. Exclusion of Central Government Municipalities

Considering the unique administrative status of China's municipalities, this study excludes the four municipalities directly under the Central Government—Beijing, Tianjin, Shanghai, and Chongqing—from the sample and re-estimates the models. The estimation results are presented in columns (7) and (8) of Table 5. After excluding the municipalities, the negative impact of the digital economy on CO₂ emissions and the positive impact on carbon emission efficiency (CEE) remain significant at the 1% level, further confirming the robustness of our regression results.

4.2.5. Excluding Other Confounding Factors

In analyzing the impact of the digital economy on CO₂ emissions (reduction) and CEE (enhancement), there exists a potential issue of mutual interference. That is, the digital economy may reduce CEs by improving CEE, or its enhancement of CEE could merely be a result of the reduction in CO₂ emissions, an undesired output. To accurately disentangle the effects of “reduction” and “enhancement”, this study controls for the impacts of CEE and CEs separately.

According to the results in columns (1) and (2) of Table 6, the variance inflation factors (VIF) for CEE are 1.10 and 5.18, respectively, both of which are between 1 and 10, indicating no collinearity issues. After controlling for CEE, the negative impact of digital economy development on CE remains significant at the 1% level of significance, demonstrating the genuine “reduction” effect achieved by the digital economy. In columns (3) and (4), the VIFs for CE are 1.47 and 1.62, respectively, also showing no collinearity issues. The regression results indicate that, after controlling for CE, the positive impact of the digital economy on CEE is significant at the 1% level, validating the effectiveness of the “enhancement” function.

Table 6. Results after excluding other confounding factors.

Variables	(1) ce	(2) ce	(3) cee	(4) cee
L.ce	0.929 *** (24.965)	0.320 *** (7.531)		
L.cee			0.860 *** (42.324)	0.439 *** (9.801)
dig	−0.024 *** (−2.997)	−0.040 *** (−7.285)	0.036 *** (11.780)	0.007 *** (3.273)
ce			−0.046 *** (−8.507)	−0.050 *** (−6.147)
cee	−0.250 *** (−1.820)	−0.405 *** (−5.647)		
Control	NO	YES	NO	YES
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
_cons	1.995 *** (5.764)	−1.744 *** (−2.609)	1.216 *** (9.542)	4.088 *** (15.298)
N	300	300	300	300
AR(1)	0.0032	0.0062	0.0032	0.0098
AR(2)	0.2814	0.4024	0.3281	0.4464
Sargan test	0.6916	0.3505	0.3300	0.7456

Note: *** $p < 0.01$; t -statistics in parentheses.

By separately controlling for CEE and CE to accurately distinguish between “reduction” and “enhancement” effects, this study not only improves the precision of our analysis but also deepens the understanding of how the digital economy facilitates low-carbon development through different pathways. This approach enables the research to provide more targeted recommendations for policy-making, while academically, it clearly demonstrates insightful perspectives on the specific mechanisms through which the digital economy contributes to low-carbon transition, highlighting the stance and contributions of this study.

5. Further Discussion

5.1. Components of the Digital Economy

To further explore the impact of the process of digital transformation on regional green development across different dimensions, this study analyzed four sub-indicators of the digital economy. According to the results in Table 7, the impact of digital infrastructure (difa) is the most significant. The regression coefficients for difa are −0.047 and 0.016 at the 1% significance level, respectively, indicating that the development of digital infrastructure

not only achieves “reduction” in regional emissions but also enhances “efficiency”. Functioning as a catalyst in the digital revolution, ‘difa’ plays a crucial role in advancing digital and informational economic growth. It stimulates the refinement and enhancement of industrial frameworks, paving the way for the progression of a high-caliber economy [89]. However, the impact of the digital inclusive finance index (difi) on CE is positive but not significant. This may suggest that implementing digital inclusive financial services requires substantial computing and data-storage resources, thus increasing electricity and energy consumption [90]. This finding is a more detailed conclusion within our research framework, highlighting the importance of in-depth study on the impact of subdivided digital development indicators on environmental economic variables.

Table 7. Results of components on low-carbon development.

Variables	difa		difi		diad		egiw	
	(1) ce	(2) cee	(3) ce	(4) cee	(5) ce	(6) cee	(7) ce	(8) cee
L.ce	0.329 *** (9.424)		0.329 *** (7.277)		0.315 *** (6.977)		0.317 *** (7.769)	
L.cee		1.012 *** (254.154)		1.022 *** (255.666)		1.015 *** (293.221)		1.017 *** (275.083)
dig	−0.047 *** (−12.820)	0.016 *** (8.451)	0.003 (0.233)	−0.006 * (−1.718)	−0.020 *** (−4.300)	0.013 *** (4.861)	−0.005 *** (−2.591)	0.004 ** (2.152)
pgdp	0.687 *** (4.856)	−0.063 *** (−2.688)	0.642 *** (3.455)	−0.050 (−1.401)	0.576 *** (3.578)	−0.077 *** (−3.448)	0.640 *** (4.139)	−0.097 *** (−3.106)
pgdp2	−0.189 *** (−4.206)	0.011 (1.608)	−0.196 *** (−3.391)	0.016 (1.471)	−0.179 *** (−3.765)	0.021 *** (3.179)	−0.190 *** (−3.926)	0.027 *** (2.934)
energy	0.775 *** (20.898)	−0.035 *** (−4.558)	0.763 *** (15.856)	−0.041 *** (−4.408)	0.800 *** (17.874)	−0.041 *** (−5.889)	0.782 *** (17.229)	−0.040 *** (−4.894)
fdi	0.026 *** (4.170)	0.010 *** (5.163)	0.019 *** (3.374)	0.011 *** (5.205)	0.021 *** (3.111)	0.009 *** (4.835)	0.020 *** (3.644)	0.009 *** (4.750)
urb	−0.318 *** (−3.982)	0.053 *** (2.615)	−0.305 *** (−5.071)	0.085 *** (4.544)	−0.287 *** (−3.959)	0.064 *** (3.034)	−0.337 *** (−4.146)	0.067 *** (3.300)
RD	−0.340 ** (−2.438)	−0.050 * (−1.822)	−0.307 *** (−2.767)	−0.056 ** (−2.107)	−0.270 (−1.495)	−0.118 *** (−4.745)	−0.280 (−1.626)	−0.073 *** (−3.271)
_cons	−4.663 *** (−15.226)	0.316 *** (4.376)	−4.260 *** (−11.753)	0.241 *** (2.731)	−4.553 *** (−14.330)	0.384 *** (6.384)	−4.460 *** (−13.001)	0.340 *** (5.643)
N	330	330	330	330	330	330	330	330
AR(1)	0.0118	0.0024	0.0097	0.0020	0.0125	0.0025	0.0116	0.0025
AR(2)	0.8301	0.3560	0.7164	0.3002	0.7599	0.3085	0.6914	0.2816
Sargan test	0.8167	0.4359	0.8380	0.3990	0.7905	0.4748	0.7812	0.4513

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; t -statistics in parentheses.

The findings in columns (5) and (6) underscore the ‘emission reduction’ and ‘efficiency enhancement’ effects facilitated by digital innovation capabilities and applications. The sub-indicator ‘diad’, standing for ‘Digital Innovation Capability and Application Degree’, measures the extent and effectiveness of integrating digital technologies into innovation processes and environmental management within industries. This integration underlines that the advancement of the digital economy has fortified local innovation and R&D capabilities, and has significantly increased the adoption of green Information and Communication Technology (ICT) products. Here, ICT products are defined as technologies, including software, hardware, and services, that are employed to collect, store, process, and disseminate information. These products are essential in driving green production processes by enhancing resource-allocation efficiency, reducing energy consumption, and facilitating sustainable industrial practices. The deepening of digitalization across the economy not only boosts societal innovation capacity but also elevates production efficiency in various sectors, contributing to a marked reduction in pollutant emissions through the strategic utilization of ICT products [91]. The results in columns (7) and (8) reveal the impact of economic growth and the number of internet workers in the field (egiw) on “emission reduction” and “efficiency enhancement”. The findings suggest that the development of the digital economy, by fostering economic growth and enhancing the employment quality of

digital technology professionals [92,93], consequently elevates local economic development levels and residents' income, strengthens the public awareness of environmental protection, and positively influences green development.

5.2. Dynamic Threshold Effect

Our study, aimed at exploring the impact of digital economy development on the low-carbon development of 30 Chinese provinces, has largely achieved its objectives. However, further discussion on the influence of green regulations and sustainable technological innovation on this relationship is both beneficial and intriguing. The existing literature has attempted similar analyses but has encountered estimation errors by treating dynamic threshold models containing lagged dependent variables as if they were static threshold models. The dynamic threshold panel regression model proposed by Seo, Kim, and Kim [75] addresses this issue effectively.

We have designated *gr* and *sti* as threshold variables to examine whether there exists a dynamic nonlinear relationship between “emission reduction” and “efficiency enhancement” under varying levels of green regulations and sustainable technological innovation. The specific regression results are presented in Table 8.

Table 8. Dynamic threshold regression results.

Variables	(1) ce	(2) ce	(3) cee	(4) cee
Lower Regime				
L.ce	0.877 *** (0.076)	1.025 *** (0.072)	0.682 *** (0.049)	0.081 ** (0.031)
dig	−0.065 ** (0.034)	−0.125 *** (0.046)	−0.080 *** (0.010)	0.019 (0.016)
gr	0.871 *** (0.129)		−0.041 (0.044)	
sti		0.077 *** (0.020)		−0.021 ** (0.011)
cons	1.569 ** (0.825)	3.684 *** (0.637)	−3.099 *** (0.554)	−0.517 *** (0.157)
Upper Regime				
L.ce	−0.121 (0.128)	−0.351 *** (0.084)	0.443 *** (0.079)	0.065 *** (0.013)
dig	0.138 *** (0.048)	0.423 *** (0.061)	0.151 *** (0.028)	0.035 ** (0.017)
gr	−1.042 *** (0.218)		−0.195 *** (0.051)	
sti		−0.142 *** (0.022)		0.060 *** (0.011)
Threshold indicator	0.763 (0.273)	5.818 *** (0.776)	0.827 *** (0.045)	3.989 *** (0.460)
Linearity test (<i>p</i> -value)	0.000	0.000	0.000	0.000
Province	30	30	30	30
Year	12	12	12	12

Notes: standard errors in parentheses. ***, ** denote significant at 1%, 5% levels, respectively.

Based on the results of columns (1) and (2) in Table 8, the *p*-values from the linear tests indicate the presence of a threshold effect. With *gr* as the threshold variable (as shown in column (1)), when *gr* is less than or equal to 0.763, the digital economy significantly inhibits CE; however, when *gr* exceeds 0.763, the coefficient turns from negative to positive. This suggests that as green regulations strengthen, businesses face increased costs due to the acquisition of new equipment and technological upgrades, which is unfavorable for controlling carbon emissions. In column (2), with *sti* as the threshold variable, the coefficients of the digital economy on CE are significant at the 1% level, but as the level

of sti increases, the coefficient likewise shifts from negative to positive. This was initially thought to be due to the diminishing marginal benefits of technology; that is, as technology advances, the marginal benefits of new innovations may decrease, making each additional innovation relatively less effective in reducing CE, aligning to some extent with Jevons Paradox. However, this contradicts our empirical findings later on (when sti is high, the development of the digital economy promotes CEE). Considering our method of measuring this indicator, we speculate that the transformation of additional innovation patents might require higher investment levels or face more implementation challenges, leading to reduced efficiency or relative increases in carbon emissions. Additionally, the development and application of sustainable technological innovation might be influenced by policy support, with policy changes potentially altering its impact on CE after reaching a certain threshold. Major technological innovations require significant investments and may exhibit diminishing marginal benefits over time, impacting carbon emissions in complex ways that underscore the need for strategic policy support.

The results in column (3) display a typical inverted-U relationship between the development of the digital economy and CEE. Before and after the threshold value of 0.827, the development of the digital economy initially inhibits the improvement of CEE, then turns to promote it. This indicates that at lower levels of green regulation, the digital economy may be unable to achieve the effect of promoting green emission reduction due to insufficient technological application and resource allocation. However, as green regulations strengthen and technological and managerial levels improve, the digital economy more effectively enhances CEE. The results in column (4) analyze the impact of the digital economy on the explained variable when green innovation is the threshold variable. The findings show that when exceeding the threshold value of 3.989, the digital economy has a more significant effect on enhancing CEE, achieving effective “efficiency enhancement”. Thus, Hypothesis 3 and part of Hypothesis 4 are validated.

This study enriches the existing theories on digital development, environmental policy, and green development by revealing the dynamic nonlinear effects of green regulation and clean-technology innovation. Particularly in the context of rapid digitalization, this is crucial for formulating effective environmental policies and promoting green innovation. Considering the complexity and multifaceted impacts of clean-technology innovation, as well as the need for different strategies and policies at various stages, this will be a focus of our future research.

6. Conclusions

The objective of this study is to analyze panel data from 30 provinces in China from 2006 to 2017, to construct a comprehensive digital economy index, and to explore the overall impact of the digital economy on low-carbon development using the System GMM and Dynamic Threshold Panel Model methods. We focus particularly on whether the development of digitalization promotes China’s green development by reducing carbon emissions and increasing carbon productivity, as well as the roles of institutional and technological factors in this process. Through an analysis from the perspectives of “emission reduction” and “efficiency enhancement”, combined with an in-depth study of the components of the digital economy, we draw the following main conclusions:

- (1) The Contribution of the Digital Economy to Dual Carbon Goals: Our research findings illuminate the significant role of digital development in reducing carbon emissions (-0.07) and enhancing carbon-emission efficiency (0.042). Digitalization aids in minimizing unnecessary resource consumption and supports the establishment of more sustainable production and consumption patterns through improved energy-utilization efficiency and market transparency. This emphasizes the importance of deepening the understanding and utilization of the digital economy’s potential in the global effort to mitigate climate change and promote sustainable development;
- (2) The Role of Digital Economy Components: Components such as digital infrastructure, innovation capabilities, application degrees, economic growth, and internet

employment reveal their beneficial contributions to reducing emissions and enhancing efficiency. However, the nuanced findings regarding the digital inclusive finance index highlight its constrained impact on environmental objectives. This discrepancy suggests that efforts to foster social and economic inclusiveness through digital means may not automatically translate into environmental benefits, possibly revealing unintended environmental side effects. This observation calls for a more granular examination of how different facets of the digital economy interact with environmental outcomes. It underscores the importance of dissecting the digital economy's influence on environmental variables to tailor more effective and comprehensive policy interventions;

- (3) **The Nonlinear Impact of Green Regulation:** The nonlinear impact of green regulation becomes apparent when the level of *gr* exceeds a threshold of 0.763, at which point the digital economy's role in reducing CE shifts from positive to negative. This suggests that overly stringent regulations may inadvertently lead to higher operational costs, hindering CE control efforts. The observed nonlinear relationship emphasizes the need for a balanced and carefully calibrated approach to formulating and implementing green regulations;
- (4) **The Role of Sustainable Technological Innovation:** With the enhancement of sustainable technological innovation levels, the digital economy plays an increasingly significant role in improving CEE—from 0.019 to 0.035. For CE, it is advised that low-carbon development policies fully consider the multifaceted role of green innovation, encouraging and supporting the research and application of green technologies, and creating a conducive policy and market environment for green products and services.

These findings offer valuable perspectives for policymakers, especially in formulating policies that integrate digital transformation with environmental sustainability. To maximize the environmental benefits of digital development, policies aimed at enhancing technology access, fostering innovation, and supporting the development of sustainable digital solutions are needed. Specifically, to do the following:

- (1) Strengthen the construction of digital infrastructure and create digital demonstration zones. By implementing a series of measures such as industrial digitalization, governance digitalization, and service digitalization in these areas, the advantages of the digital economy in promoting green development can be fully utilized;
- (2) To optimize the environmental impact of the digital economy, it is essential to conduct targeted research that informs policy adjustments. Policymakers should prioritize studies on the specific effects of digital economy segments, including digital finance, on sustainability. This research should guide the development of adaptive policies that both support digital inclusiveness and address potential environmental side effects. By fostering a dynamic policy environment that evolves with emerging findings, we can ensure that the digital economy advances economic, social, and environmental goals in unison;
- (3) To harness the digital economy's potential for environmental benefits effectively, policies should aim for a balanced approach that identifies the optimal level of green regulation. This balance should encourage emission reductions without imposing significant financial burdens on businesses. Alongside, providing targeted support for businesses—especially SMEs—through financial incentives and technical assistance is crucial. This integrated strategy ensures regulations are both effective and adaptable, facilitating a smooth transition towards greener practices and sustainable growth;
- (4) Governments should create a supportive ecosystem that incentivizes the development and application of green technologies. This can be achieved by combining financial incentives (such as tax breaks and grants), fostering public–private partnerships for research and development, and creating favorable market conditions for green products. Additionally, adjusting regulatory frameworks to encourage the adoption of sustainable technologies and providing platforms for knowledge exchange can significantly accelerate green innovation. This integrated approach aims to reduce

barriers to investment in green technologies, encourage collaborative innovation, and ensure a market that rewards environmental sustainability;

- (5) We recommend that governments and financial regulatory bodies establish stricter standards for disclosure and transparency, and implement dynamic regulation and continuous evaluation mechanisms. Such measures aim to provide more objective and fair information, ensuring that green financial resources are truly directed towards projects with a positive environmental impact.

It is important to acknowledge that our study's scope is limited to a macro-level analysis within a specific national context, without international comparisons. However, the implications of our findings still hold significant relevance, especially for countries actively pursuing low-carbon development strategies. Future research can broaden the scope of this research with the following guidelines: further refine digital economy indicators to more accurately understand and quantify the specific impacts of digitalization on the environment; and develop and improve economic models to better capture the threshold effects of green technology innovation, including the prediction of diminishing marginal benefits and market saturation points.

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Appendix A

Green Regulation (ER): Following the approach of Zhang, Liu, Wang, and Zhou [60], the calculation process is as follows:

First, normalize the environmental performance of pollutant j in province i in year t :

$$n_j ep_{it} = \frac{ep_{ijt}}{\frac{1}{30} \sum_{t=1}^{30} ep_{ijt}} \quad (A1)$$

where ep_{ijt} is the ratio of actual increase in industrial production value to the emission of pollutant j in province i in year t . Then, to eliminate differences between dimensions, the final equation is constructed as follows:

$$er_i = 1 / \frac{1}{3} (\sum_{j=1}^3 ep_{it}) \quad (A2)$$

Sustainable Technological Innovation (STI): In this paper, the number of green patent authorizations in each province, retrieved according to the classification numbers of the International Patent Classification Green Inventory (IPC Green Inventory), is used as an indicator to measure sustainable technological innovation.

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