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How Does the Digital Economy Affect Carbon Emission Efficiency? Evidence from Energy Consumption and Industrial Value Chain

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Abstract: China is confronted with the dual constraints of economic transformation and carbon emission reduction. As the digital economy is a key force in promoting economic transformation and optimizing industrial structure, it is crucial to analyze the digital economy's impact on carbon emission reduction from the perspective of energy consumption and industrial value chain implications. We selected data from 251 prefecture-level cities and above in China from 2011 to 2019 as research samples, measured the development level of the digital economy using the entropy value method, and constructed relevant regression models based on two-way fixed effects, intermediary analysis, and moderation analysis. The research reveals that: (1) The digital economy has a significant contribution to carbon emission efficiency, and there are significant regional heterogeneity and city size differences; (2) The digital economy can improve carbon emission efficiency by reducing energy consumption. (3) From a value chain perspective, industrial structure rationalization weakens the carbon emission efficiency improvement effect of the digital economy to a certain extent, whereas industrial structure upgrading obviously enhances the carbon efficiency improvement effect of the digital economy. The above findings enrich the research in the field of digital economy and environmental governance, contribute to a more comprehensive understanding of the mechanisms by which the digital economy affects the carbon emission efficiency, as well as provide policy implications for enhancing the use of the digital economy in the regional energy consumption and industrial value chain.

Keywords: digital economy; carbon emission efficiency; industrial structure; energy consumption; industrial value chain; mediation model; moderation model

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1. Introduction

The effects of climate change on the sustainable growth of human society are significant. The Paris Agreement establishes the objective of managing the global temperature increase: accomplishing the goal of reducing global average temperature rise to no more than 2 °C and seeking to maintain it under 1.5 °C in order to safeguard the earth's ecological security [1]. To attain this long-term goal, nations must immediately peak their greenhouse gas emissions and contribute to the realization of carbon neutrality by the middle of this century. With China being the largest emitter of carbon dioxide and having the most comprehensive range of industries, China's effective promotion of low-carbon transition development is an obvious choice for deploying carbon peaks and carbon neutrality. A binding target of 13.5% reduction in energy consumption and 18% reduction in carbon emissions has been set for China under the 14th Five-Year Plan. In this situation, it is necessary to improve the efficiency of carbon emissions, achieving more economic growth with less energy and the same amount of carbon emissions, push for a complete low-carbon transformation in economic and social fields, and follow a green, low-carbon, high-quality development path to meet the "double carbon" target on time.

Currently, the digital economy is becoming increasingly influential in restructuring factor resources, changing economic structures, and transforming the competitive environment. According to the data released in *the Report on the Development of China's Digital Economy (2022)*, the digital economy in China achieved a new high in 2021, with its size reaching 45.5 trillion yuan with a nominal growth rate of 16.2%, 3.4% higher than the nominal growth rate of GDP, and accounting for 39.8% of GDP [2], strengthening its position in the national economy as well as playing an increasingly important supporting role.

Although the digital economy can provide long-term benefits to economic development, its possible environmental implications have also garnered the attention of numerous academics. In terms of theoretical and empirical studies, there is still a lack of direct discussion on the impact of the digital economy on the efficiency of carbon emissions, but relevant studies on the impact of the digital economy, especially on carbon emissions, provide references and inspirational implications for this paper. On the one hand, some scholars believe that the digital economy is an effective way to mitigate carbon emissions. They argue that the digital economy is providing a new impetus for intelligent management of the environment, with information technology at its core, and has a positive effect on environmental pollution control by functioning as informal environmental regulation [3,4]. Simultaneously, the extrusion effect of the digital economy can effectively promote the transformation and upgrading of the regional industrial structure, further restrain the development of high energy-consuming and high-polluting industries, and thus accelerate the improvement of environmental quality [5,6]. On the other hand, an opposite viewpoint on the impact of the digital economy on carbon emissions has gained significant attention. Proponents of this view believe that the development of the digital economy does not reduce energy consumption, but rather increases it, and that the energy growth effect of the digital economy may have outweighed the energy reduction effect [7]. Moreover, the expansion of the digital economy increases the size of the economy, which in turn increases energy consumption and carbon emissions [8]. These contradicting findings have piqued the interest of academics in researching the impact of the digital economy on carbon emissions.

Research on carbon emission efficiency is mainly focused on the measurement of carbon emission efficiency among different regions and industries, and the analysis of the influencing factors of carbon emission efficiency [9,10]. Research on digital economy and carbon emission mainly focuses on the digital economy's impact on carbon emission [11,12], the link between the digital economy and carbon emission performance [13], and the impact of internet development on carbon emission efficiency [14]. However, few scholars have argued for a possible direct impact relationship between carbon emission efficiency and the digital economy, and there is a lack of further evidence to support the relationship in terms of value chain and energy consumption. This paper therefore seeks to bring the variety of digital economy development into the research framework of the impact factor theory for carbon emission efficiency in order to determine whether the digital economy influences carbon emission efficiency, if such an effect exists. What is the mechanism of industrial value chain and energy consumption in the process if this effect does exist? To answer the above questions, this paper combines the distinctive characteristics of the digital economy and constructs a theoretical analysis framework from the perspective of carbon emission efficiency. Based on this framework, the digital economy and carbon emission efficiency levels of 251 prefecture-level and above cities in China were measured from 2011 to 2019, and the impact of the digital economy on urban carbon emission efficiency and its mechanism of action were empirically examined. The findings indicated that the digital economy greatly improved carbon emission efficiency in the region, with the reduction of energy consumption and the improvement of industrial value chains being among the most significant mechanisms of effect.

As a crucial component of high-quality development, the influence of the digital economy on economic growth and ecological environment is gaining increasing attention. As a typical developing country, examining the contribution of China's digital economy

to enhancing carbon emission efficiency can provide developing countries with theoretical support for enhancing the carbon emission reduction capacity of the digital economy and achieving "economic growth—environmental protection" win-win development. The original study's potential marginal contributions included the following three aspects: (1) This paper empirically tested whether the digital economy had a positive impact on carbon efficiency using data from prefecture-level municipalities, providing new empirical evidence for research related to the digital economy and environmental quality, especially in the area of carbon emissions. It also offered potential policy references for green development in China; (2) A comprehensive evaluation index system at the municipal level was constructed, therefore enhancing the measurement approach. To comprehensively reflect the development of the digital economy in Chinese cities, comprehensive digital economy indicators were constructed with the internet as the core, and the characteristics of digital economy development and the influence relationship between the digital economy and carbon emission efficiency were discussed in greater detail. (3) We explored the intrinsic mechanism of the digital economy affecting carbon emission efficiency, and used energy consumption as a mediating variable to analyze the transmission path, effect size and heterogeneous differences of the digital economy on carbon emission efficiency improvement, and clarify the policy focus points for promoting the low-carbon development of the digital economy.

The remainder of this paper is structured as follows. Section 2 presents the relevant research hypotheses through literature analysis. Section 3 provides an overview of the research data and methodology. Sections 4 and 5 explain and analyze the empirical results. Section 6 elaborates the conclusions and policy recommendations of this study.

2. Research Hypotheses

The impact routes of the digital economy on carbon emission efficiency may be analyzed from two perspectives: the direct impact road from the standpoint of digital economy development, and the indirect impact path from the standpoints of energy consumption and the industrial value chain. The influence mechanism of the digital economy on carbon emission efficiency is depicted in Figure 1.

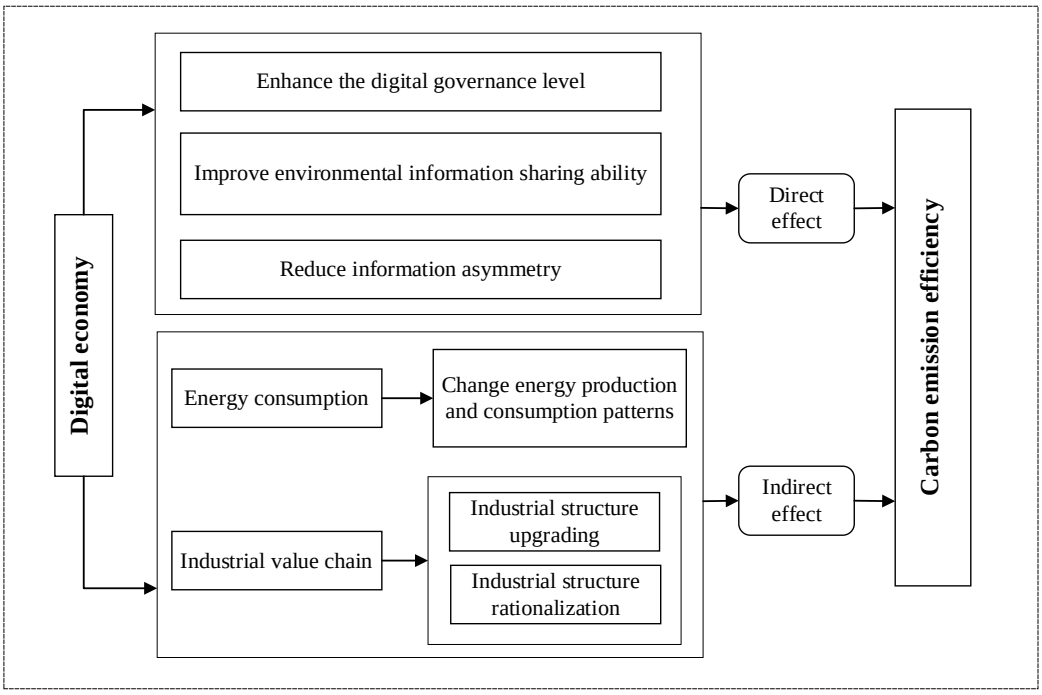


Figure 1. Mechanism analysis between digital economy and carbon emission efficiency.

2.1. The Direct Impact of the Digital Economy on the Efficiency of Carbon Emissions

Numerous scholars have studied the energy and environmental effects of the digital economy's development and found that the rapid development of the digital economy exemplified by the internet not only results in rapid economic growth, but also contributes to significant improvements in environmental performance [15,16]. It has been determined that the rapid expansion of the digital economy, as demonstrated by the internet, brings not only quick economic growth but also major improvements in environmental performance. The rise of the digital economy has a substantial impact on carbon emissions, the most evident signal of change within the framework of climate change. On the one hand, the development of the digital economy drives up the level of digital technology, the application of digital technology in environmental protection has changed the traditional environmental monitoring model and method by combining various sensors and computer technology to create a comprehensive network information collection system, realizing the integration of data collection and transmission and management, reducing the cost of monitoring technology, and enhancing the monitoring capability of real-time assessment of environmental conditions [17]. The efficient sharing of environmental information facilitates effective resource deployment, compensates for the deficiencies of traditional regulatory tools in a targeted manner, provides data support to enhance environmental regulation and enforcement, and thereby improves pollution management [18]. Moreover, the development of digital technology offers new options and avenues for business information disclosure, thereby mitigating the negative effects of information asymmetry [19]. In addition, it strengthens the competition mechanism of elimination of winners and losers in the market environment, forcing enterprises with high pollution and high emissions to invest more in research and development to achieve an efficient use of resources and low carbon and sustainable development of the city [20]. On the other hand, the development of the internet has brought about changes in connectivity and communication, accelerated the speed of information transfer, enriched access to information, provided more opportunities for knowledge sharing, use and re-creation, enabled traditional industries to take advantage of the penetration and derivation of digital technology for industrial upgrading, promoted the process of technical catch-up and economic convergence, as well as the development of intelligent and environmentally friendly industries [21], and reduced energy consumption and pollutant emissions [22]. In addition, the efficiency of carbon emission is improved. In summary, we propose Hypothesis 1.

Hypothesis 1 (H1). *The digital economy positively affects carbon emission efficiency.*

2.2. Indirect Impact of the Digital Economy on Carbon Efficiency

2.2.1. Digital Economy and Carbon Efficiency: The Energy Consumption Perspective

Energy consumption is a key driver of carbon emissions, which include the consumption of natural resources such as coal, oil and natural gas [23]. In the context of the expansion of the digital economy, an increasing number of studies have proven the function of the use of digital devices and processes that might increase energy efficiency in many industries [24–26]. Specifically, in promoting the integration of traditional energy companies with digital enterprises, the use of digital technologies has significantly improved the operational efficiency of oil and gas companies. Additionally, the latest information technology has been utilized to integrate energy and digital technologies in order to build a new energy ecosystem, change the way energy is produced and consumed, optimize the energy mix, accelerate the energy transition, and improve carbon emission performance [27,28]. The digital economy accelerates urban processes and brings about the development of public transportation and renewable energy [29], which helps to capitalize on the economies of scale of public infrastructure and prevent environmental damage [30]. Simultaneously, the extensive use of big data analysis can effectively promote the construction of the global energy internet, which can effectively improve the efficiency of energy resource allocation, enable the development and consumption of clean energy to reach scale, and gradually

replace fossil fuel energy, which is conducive to reducing carbon dioxide emissions and can improve carbon emission efficiency [12,31].

Conversely, it has been proposed that rapid urban expansion and development increases intensive urban economic activities caused by housing, transportation and recreation [32], which increases energy demand and leads to more carbon emissions [33], which reduces the regional carbon efficiency, and the energy consumption associated with the creation of digital infrastructure itself may negate any possible energy savings. It is argued that the digital economy based on communication technologies has energy-intensive qualities, and a huge quantity of infrastructure construction will consume more energy resources in the early stages of digital economy development [7]. In addition, data creation, process, storage, and movement depend on resources such as water, electricity, and metals, and as the scale of use of digital services and products continues to expand, the environmental pollution caused by e-waste during use and carbon emissions also increase [34]. Collard et al. and Longo et al. also believe that the usage of ICT has resulted in an increase in electricity consumption and that communication technologies have not significantly improved the environment [35,36]. Therefore, we argue that the digital economy can affect carbon efficiency through influencing energy consumption, and in this paper, we propose the following mediation hypothesis.

Hypothesis 2 (H2). *Energy consumption plays a mediating role between the digital economy and carbon efficiency.*

2.2.2. Digital Economy and Carbon Efficiency: Industrial Value Chain Perspective

In the context of the rapid development of information technology, the internet, with its characteristics of openness, collaboration and sharing, has gradually become the most important production application tool, and its integration with traditional production factors and resources has promoted industrial upgrading [37]. Gereffi et al. suggest that industrial upgrading can be seen as a process of climbing up the value chain or between value chains for firms and the whole industry in the region [38]. The productivity dividend brought by the deep integration of new generation communication technology and advanced manufacturing technology can significantly break the innovation bottleneck of each link in the industrial chain, thus breaking the "low-end locking" trap of the industrial value chain and making the industrial structure develop from low-level to high-level forms with inter-industrial upgrading [39], and the degree of change from low to high value-added industries can directly reflect the quality and level of development of the industrial value chain.

The inter-industrial upgrade will, to a certain extent, diminish the good impact of the digital economy's development on reducing carbon emission efficiency. The rapid emergence and evolution of digital technology has created a new opportunity for the industrial structure to transform from a factor-driven to an innovation-driven mode. This can help boost sectoral productivity and improve the industrial value chain [40]. Moreover, digital network platforms can promote resource sharing among industries and fields via scale and competition effects, optimize traditional industrial production and sales methods, strengthen the market competition mechanism, eliminate backward production capacity, and force backward and low-end industries to upgrade [41]. Existing scholars have argued that inter-industrial upgrading might successfully cut carbon emissions via a variety of techniques [42,43]. In the process of developing industrial structure in a green direction, the fossil energy-based energy structure will be significantly enhanced, especially for energy-intensive and carbon-emitting industrial sectors, and digital technology will reduce the demand for energy and materials, which can effectively improve energy efficiency and resource allocation efficiency, thereby reducing carbon emissions. Therefore, we believe that inter-industry upgrading is an important element in industrial value chain upgrading, as the impact of the digital economy on carbon emission efficiency will be significantly influenced by industrial structure value-chain upgrading. Furthermore, we

divide the inter-industry upgrading into two dimensions, industrial structure advanced and industrial structure rationalization. The industrial structure upgrade process involves increasing the number of high-value-added industries. This process is carried out to improve the overall structure of the facility. The second is industrial structure rationalization; the higher the degree of inter-industry coordination, the higher the degree of industrial structure rationalization.

From the above, we propose the following hypotheses.

Hypothesis 3a (H3a). *Industrial structure upgrading plays a moderating role between digital economy and carbon efficiency.*

Hypothesis 3b (H3b). *Industrial structure rationalization plays a moderating role between digital economy and carbon efficiency.*

3. Model

3.1. Method

To test the above research hypotheses, a two-way fixed-effects model is first constructed for the direct transmission mechanism.

$$eff_{it} = \alpha_0 + \alpha_1 digital_{it} + \alpha_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

In Equation (1), eff_{it} represents the carbon emission efficiency of city i at time t, $digital_{it}$ is the digital economy development index of city i in period t, X_{it} is a vector that represents the remaining control variables, μ_i is the individual fixed effect, δ_t refers to the time-fixed effect, and ε_{it} denotes the random error term.

Besides the direct effect embodied in Equation (1), this study also explored the possibility that the consumption of energy can be a factor mediating the digital economy and carbon emissions. Referring to the stepwise method proposed by Baron and Kenny (1986) for testing mediating effects [44]: the coefficient α_1 significance of the model (1) of digital economic development index (*digital*) on carbon emission efficiency (eff) passed the test, so we constructed linear regression equations for *digital* on the mediating variable energy consumption (*energy*), as well as regression equations for *digital* and the mediating variable *energy* on eff. The mediation effect will be judged by the significance of regression coefficients such as β_1, γ_1 and γ_2. The following is the specific form of the regression model:

$$energy_{it} = \beta_0 + \beta_1 digital_{it} + \beta_2 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

$$eff_{it} = \gamma_0 + \gamma_1 digital_{it} + \gamma_2 energy_{it} + \gamma_3 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

Further, this section adds the interaction term of industrial structure upgrading (*insu*) and industrial structure rationalization (*inso*) with digital economy development index (*digital*) to test the role of industrial structure moderation between digital economy and carbon emission efficiency, the significance of the regression coefficients such as η_3 and η_7 will be used to determine whether the moderating effect exists.

$$eff_{it} = \eta_0 + \eta_1 digital_{it} + \eta_2 insu_{it} + \eta_3 digital_{it} \times insu_{it} + \eta_4 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (4)$$

$$eff_{it} = \eta_0 + \eta_5 digital_{it} + \eta_6 inso_{it} + \eta_7 digital_{it} \times inso_{it} + \eta_8 X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (5)$$

3.2. Variables

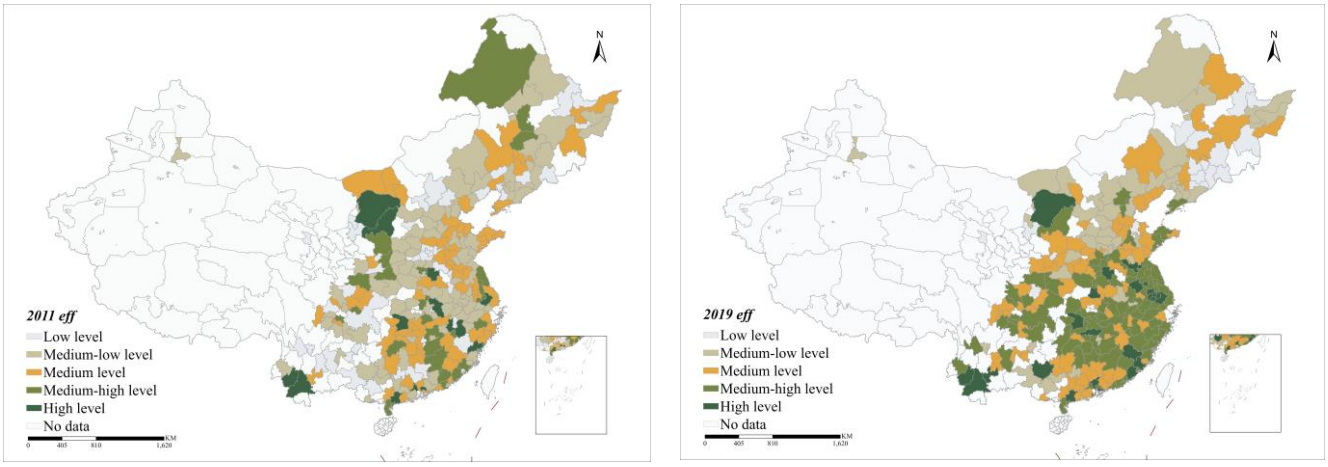
3.2.1. Dependent Variable

The explanatory variable studied in this paper is carbon emission efficiency (eff). This research is based on the super-efficient SBM model proposed by tone [45], which incorporates labor input, capital stock, and energy consumption as input indicators, GDP as desired output and carbon emissions as non-desired output, as stated in Table 1. (1) Labor

input is indicated by the number of employees in each prefecture-level city at the end of the year. (2) The estimation of capital stock is mostly calculated using the perpetual inventory method at constant prices, and this part draws on Zhang's approach [46], which adopts a discount rate of 9.6% to calculate the capital stock at the end of each year from 2011 to 2019, using the year 2000 as the base period, the calculation formula is $K_{it} = K_{it-1}(1 - \delta_{it}) + I_{it}$, where K_{it} is the capital stock of region i in year t. I_{it} is the fixed asset investment of region i in year t. δ_{it} is the depreciation rate. (3) The direct energy consumption of the city mainly includes natural gas and liquefied petroleum gas, whereas the indirect energy consumption mainly includes electricity consumption, which will be converted into standard coal by referring to the *General rules for calculation of the comprehensive energy consumption GBT2589-2020* because units are not uniform. (4) The estimation of carbon dioxide emissions is based on the approach of shan, according to *the Intergovernmental Panel on Climate Change (IPCC)* guidelines on the allocation of greenhouse gas emissions, carbon emissions are calculated for 17 fossil fuel combustion and cement production-related process emissions for 47 socioeconomic sectors [47]. Figure 2 shows the spatial distribution of carbon emission efficiency indicators, and most cities show an increasing trend of carbon emission efficiency. Due to the limitation of space, this paper only provides the calculation results of two years.

Table 1. Evaluation system of carbon emission efficiency.

Input/Output	Indicators	Definition	Units
Input	Labor force	Number of employees in the unit at the end of year	10,000 people
	Capital stock	Total fixed assets at the end of year	10,000 yuan
	Energy consumption	Total energy consumption of natural gas, liquefied petroleum gas and electricity at the end of year	10,000 tons of coal
Desirable output	Economic output	Gross domestic product (GDP) at the end of year	10,000 yuan
Undesirable output	Carbon emission	Carbon emission at the end of year	10,000 tons



(**a**) (**b**)

Figure 2. China's carbon emission efficiency. (**a**) Spatial distribution in 2011; (**b**) Spatial distribution in 2019.

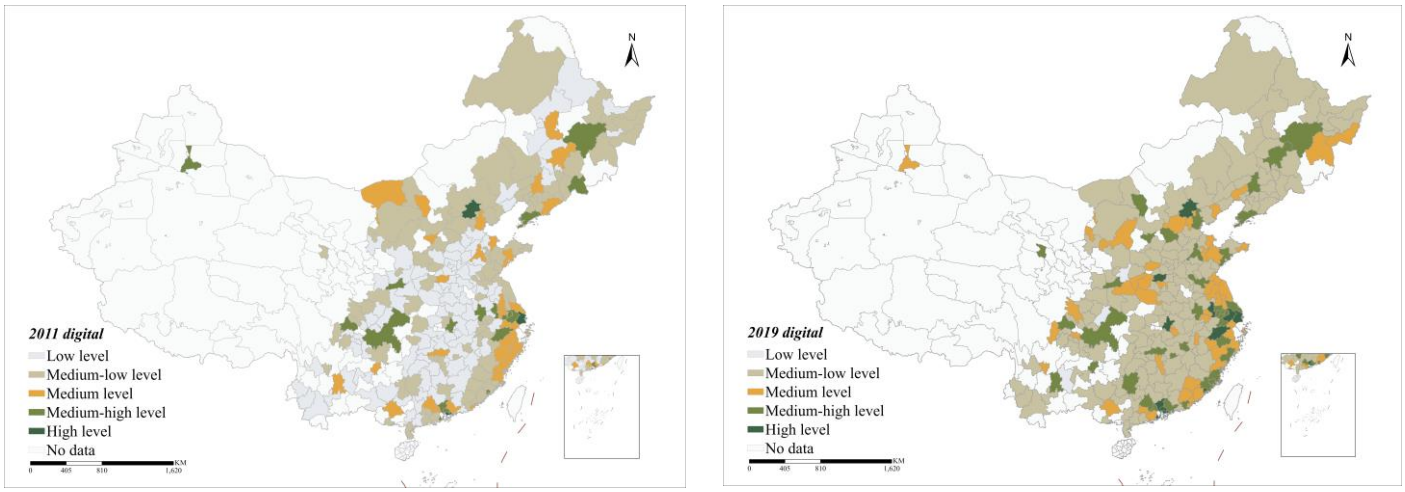
3.2.2. Independent Variable

The digital economy index (*digital*) is the key explanatory variable for this article. Currently, there is a paucity of relevant research regarding the precise measurement of the digital economy, and academics have not yet developed a recognized evaluation system. Based on the study findings on the definition of digital economy, the design of an index system, and measurement methodologies, this work utilizes the availability of

city-level data and the methodology of Zhao et al. to examine the economic and financial characteristics of the digital economy [48], measuring the development level of digital economy from internet development and digital finance. Considering the postal express business has increased fast in recent years along with the rapid development of e-commerce, the promotion of internet popularity on the scale of local postal express is relatively stronger than other factors [49]. In addition, the expansion of the digital economy has presented technology inventors with increasingly specialized business model difficulties, which in part encourages technology innovation [50]. In this article, internet penetration rate, internet-related practitioners, internet-related output, cell phone penetration rate, postal service output, and technological innovation capability are considered as indicators of internet development level. For digital finance development indicators, the Digital Financial Inclusion Index of China is used, which is compiled by *the Institute of Digital Finance Peking University* and *Ant Financial Group Holdings Limited*, comprehensively measuring three aspects: breadth of digital finance coverage, depth of use, and degree of digitalization [51]. The specific description is shown in Table 2. As an objective weighting method, the entropy method has a stronger objectivity, so this paper processes the data of the above indicators through the entropy method to obtain the digital economy index (*digital*). Figure 3 shows the trend of China's digital economy development level by cities. In general, digital economic development is more advanced in 2019 than it was in 2011.

Table 2. Evaluation system of the digital economy development index.

Primary Indicators	Secondary Indicators	Tertiary Indicators	Indicator Description	Unit	Indicator Properties
Digital economy development index	Internet development level	Internet penetration rate	Number of Internet access users per 100 people	household	+
		Internet-related practitioner	Computer services and software industry employees accounted for the proportion of urban unit employees	%	+
		Internet-related output	Total telecom services per capita	Yuan	+
		Cell phone penetration rate	Number of cell phone subscribers per 100 people	household	+
	Digital technology application	Postal operations output	Total postal services per capita	Yuan	+
		Technology innovation capability	Number of digital economy-related invention patent applications in the current year	Pieces	+
	Digital finance development level	Digital financial inclusion	Digital financial inclusion index of China	–	+



(**a**) (**b**)

Figure 3. China's digital economy. (**a**) Spatial distribution in 2011; (**b**) Spatial distribution in 2019.

3.2.3. Control Variables

To mitigate omitted variable bias as much as possible, the article further controls for a series of variables that affect the efficiency of urban carbon emissions. (1) Economic growth ($pgdp$), as measured by GDP per capital [50,52]; (2) Population density (pop), the ratio of total population to administrative area is chosen to represent population density [53,54]; (3) Environmental regulation (er), this paper collates all *Report on the Work of the Government* in prefecture-level cities from 2011–2019 by hand, sub-phrase the texts, count the frequency of environment-related words (Environment-related terms specifically include: pollution, emission reduction, prevention, ecological protection, low carbon, PM2.5, pm2.5, haze, emissions, emissions, air, blue sky defense war, pm10, PM10, green, environmental protection, particulate matter, monitoring, energy saving, dust, noise, tailpipe, emissions, environmental protection, forest coverage, soot, atmosphere, sulfur dioxide, SOD, ozone, sewage, SO_2, binding indicators, wastewater, recycling, water conservation, nitrogen oxides, energy, clean, unit GDP, chemical oxygen demand, energy consumption, ecological construction, green water and green mountains, low carbon, pollution control, waste gas, carbon dioxide, energy saving, ecology) and their proportion to the total number of words in the report, so as to characterize the environmental regulation [55]; (4) Foreign direct investment (fdi), as measured by the ratio of the annual actual foreign direct investment as a percentage of GDP [56,57]; (5) Financial development ($finan$), as calculated by the ratio of loan balances in financial institutions to regional GDP at the end of the year [58]; (6) Urban transportation network construction ($trans$), as measured by the road area per capita [59].

3.3. Data Sources and Descriptive Statistics

This research examines Chinese prefecture-level and higher cities between 2011 and 2019. Due to the challenges of incomplete data or poor data quality in some cities, the panel data of 251 cities are finally retained, and a small amount of missing data are compensated by linear interpolation. China City Statistical Yearbook, China Energy Statistical Yearbook, China Macro Economy Database, prefecture-level Municipal Statistical Bulletin, prefecture-level Report on the Work of the Government, website of Institute of Digital Finance Peking University, Carbon Emission Accounts and Datasets (CEADs), CSMAR database are the sources for the data used in this study. In addition, this paper uses the annual average price of RMB to USD exchange rate from the National Bureau of Statistics to adjust the total of foreign direct investment; the standard coal conversion is based on the general rules for calculation of the comprehensive energy consumption GBT2589-2020. In order to reduce the dispersion of the data, this paper logarithmically processes certain indicators. The results of descriptive statistics for the major variables in this work are presented in Table 3.

Table 3. Descriptive statistics of the variables (before logarithm).

Variables	Symbol	Obs	Mean	Std. Dev.	Min	Max
Carbon emission efficiency	*eff*	2259	0.45	0.19	0.17	1.38
Digital economy index	*digital*	2259	0.05	0.05	0.01	0.71
Economic growth	*pgdp*	2259	53,292.50	34,022.71	9773.00	467,749.00
Population density	*pop*	2259	3719.28	2536.95	179.00	15,055.00
Environmental regulation	*er*	2259	0.01	0.01	0.00	0.15
Foreign direct investment	*fdi*	2259	0.02	0.02	−0.03	0.20
Financial development	*finan*	2259	0.96	0.55	0.12	7.45
Urban transportation network	*trans*	2259	5.14	6.35	0.21	73.04

4. Results

4.1. Baseline Regression Results

Table 4 displays the results of the linear regression estimation of the digital economy affecting urban carbon emissions' efficiency. Models 1 and 2 show the results of fixed-effects model tests with and without control variables. Despite the absence of control factors,

the digital economy can still help to improve carbon emission efficiency at a significant level of 1%. This is consistent with the conclusion of Hypothesis 1. Furthermore, there is a substantial positive correlation between the level of economic growth and carbon emission efficiency in Model 2, indicating that regional carbon emission efficiency has been effectively increased as a result of urban economic growth and economically developed regions with advanced production technology. This is probably because economic growth in China is gradually shifting from extensive to low-carbon model [10]. In contrast, the level of financial development and urban transportation network has a negative correlation with urban carbon emission efficiency. This may be because the financial development and the construction of the urban transportation network significantly accelerated the degree of urban development and expansion, which aggravated the total amount of carbon emissions in the region, thereby decreasing the efficiency of carbon emissions in a certain period of time [60,61].

Table 4. Baseline regression results and instrumental variable test results.

	Model 1 *eff*	**Model 2** *eff*	**Model 3** *digital*	**Model 4** *eff*
digital	0.7549 ***	0.5905 ***		3.2639 ***
	(7.9560)	(6.2796)		(3.4517)
distance × *mean_digital*			−0.0004 ***	
			(−7.4312)	
ln*pgdp*		0.1375 ***		0.0667
		(8.8389)		(1.3197)
ln*popud*		0.0028		0.0027
		(0.4188)		(0.4462)
er		−0.3187		0.3380
		(−0.9814)		(0.9002)
fdi		−0.1314		0.1350
		(−0.6896)		(0.6190)
finan		−0.0258 **		−0.0419
		(−2.5714)		(−1.6251)
ln*trans*		−0.0491 ***		−0.0132
		(−4.8218)		(−0.7097)
Constant	0.3960 ***	−0.9827 ***	0.0330 ***	−1.7502 ***
	(64.0975)	(−5.6587)	(18.6782)	(−3.6478)
KleibergenPaap rk LM statistic				27.57
				[0.000]
KleibergenPaap rk Wald F statistic				26.74
				{16.38}
Observations	2259	2259	2259	2259
Year	YES	YES	YES	YES
City	YES	YES	YES	YES
Adjust R^2	0.131	0.181	0.361	0.685
F	66.58	50.89	170.3	76.86

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels. The figures in () are t statistics and in [] is P value of the corresponding test statistics. The critical value at the level of 10% critical values of Kleibergen-Paap rk Wald F test is within {} [62].

The findings of the baseline regression indicate a substantial positive correlation between the digital economy and carbon emission efficiency, and the development of regional digital economy contributes to the improvement of local carbon emission efficiency. The digital economy indicator system constructed in this paper may have measurement errors due to the availability of data, resulting in correlations between digital economy development indicators and unobservable factors affecting carbon emission efficiency. Besides, the reverse causality may exist between digital economy development and carbon emission efficiency.

This paper attempts an instrumental variable approach to mitigate the endogeneity problem. We use the spherical distance between each city and Hangzhou (The research

methodology drawn from this paper selects the geographic feature of spherical distance from cities at all levels and above to Hangzhou as an instrumental variable. This instrumental variable is correlated with the degree of digital economy development in the region. The growth of digital finance exemplified by Alipay started in Hangzhou; thus, Hangzhou is the leading city in terms of digital economy development, and it is reasonable to predict that the closer a city is geographically to Hangzhou, the greater the level of digital economy development) as an instrumental variable (*distance*), and interact *distance* with the mean value of the digital economy development index (*mean_digital*) at the national level in the corresponding year as a new instrumental variable with time-varying effects [63]. Model 3 of Table 4 demonstrates that the estimated coefficient of the instrumental variable is −0.0004, which is statistically negative at the 1% significantly level. It implies that the more distant from the digital economy development center, the lower the level of the digital economy development, which is in line with expectations. After considering the endogeneity of the variables, the results of model (4) indicate that the digital economy still has a significant contribution to the efficiency of carbon emissions, which further supports the conclusion obtained from the benchmark regression, indicating that the improvement of the development level of the digital economy contributes to the improvement of carbon emission efficiency.

4.2. Robustness Tests

4.2.1. Dynamic Panel Regression

Different models have been selected to analyze and test the impact of the digital economy on carbon emission efficiency. One of the biggest issues in the estimation process of the model is the treatment of the endogeneity problem, as this endogeneity is caused by the system itself, which is identical to the dynamic panel data in this respect. This paper further uses the dynamic panel regression to test the robustness of the benchmark regression. The System Generalized Method of Moments (SYS-GMM) estimation is commonly utilized in dynamic panel data estimations to address endogeneity issues, and the SYS-GMM is compared to the difference Generalized Method of Moments (difference-GMM) by introducing level equations to reduce estimation errors. In order to evaluate the model, this study employs a two-stage SYS-GMM estimation approach; the estimation results are presented in Table 5. As can be seen from Model 1, AR (1) test rejects the null hypothesis at the 1% significance level, and AR (2) test cannot reject the null hypothesis, indicating that the model does not have higher-order serial correlation. The p-value of the Hansen test is 0.2080, which satisfies the over-identification test, indicating that the instrumental variables selected in this paper are reasonable and valid. The results from the SYS-GMM method demonstrate that the coefficients of the digital economy on carbon emission efficiency are significantly positive at the 1% level, which is consistent with the results of the baseline regression, supporting the robustness of the baseline regression.

Table 5. Robustness test results.

	Model 1 *eff*	**Model 2** *eff*	**Model 3** *eff*	**Model 4** *eff*
L.eff	0.8280 ***			
	(21.2600)			
Score	0.3076 **	0.5905 ***	0.6276 ***	
	(2.0572)	(6.2796)	(5.5234)	
L.Score				0.9311 ***
				(8.8773)
Control variables	YES	YES	YES	YES
Constant	−0.5737	−0.9827 ***	−0.9797 ***	−1.2033 ***
	(−1.5285)	(−5.6587)	(−5.5661)	(−6.7456)
Observations	2008	2259	2223	2008
Year	YES	YES	YES	YES

Table 5. *Cont.*

	Model 1 *eff*	**Model 2** *eff*	**Model 3** *eff*	**Model 4** *eff*
City	YES	YES	YES	YES
Hansen-p	0.2080			
AR (1)-p	0.0000			
AR (2)-p	0.3542			
F		50.89	47.50	55.69
Adjust R^2		0.1808	0.1689	0.2044

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels. The figures in () are t statistics or z statistics.

4.2.2. Controlling Provincial Fixed Effect

Considering the possible changes in the macro-systemic environment caused by the widespread expansion of the digital economy, this section mitigates the possible changes of the digital economy development by introducing province-fixed effects and interaction effects between provinces and years. The estimation results of Model 2 in Table 5 show that the digital economy still plays a positive role in enhancing the carbon emission efficiency after considering the systematic changes of macro factors.

4.2.3. Excluding Municipalities Directly under the Central Government

Since Beijing, Tianjin, Shanghai, and Chongqing are under the direct jurisdiction of the central government, the administrative status is relatively special compared to other prefecture-level cities. In order to avoid the influence of administrative variables on the findings of the baseline regression, this section excludes the four municipalities from the full sample and then performs the regression test again. The estimation result in Model 3 of Table 5 shows that the regression coefficient is 0.6276, which is significantly positive at the 1% level, proving the robustness of the baseline regression results.

4.2.4. Replacing the Core Explanatory Variable

In consideration of the time required for the development of the digital economy to influence low-carbon development in the region by building infrastructure and restructuring industries, as well as to further mitigate the possible reverse causality, this paper treats the digital economy variables with a one-period lag. As shown by Model 4 in Table 5, after the lagged one-period treatment, the digital economy still contributes significantly to the carbon emission efficiency in the region at 1% level, which supports the results of the baseline regression.

4.3. Heterogeneity Analysis

Due to disparities in resource endowments and phases of development, there are obvious heterogeneous characteristics in the regional distribution of both digital economy development levels and carbon emission efficiency levels. This study examines regional differences in the impact of the digital economy on carbon emission efficiency at the city level from two perspectives: sub-regional and city-level, in light of the potential spatial heterogeneity of the impact of digital economy development on urban carbon emission efficiency. The regional classification is separated into four regions based on the regional location of each city in the province: northeastern, eastern, central and western regions. For the classification of city levels, the sample of central cities in this paper mainly includes municipalities directly under the central government, sub-provincial cities and provincial capitals, and other prefecture-level cities as peripheral cities. Before regression testing, descriptive statistics are performed on the disparities in digital economy development and carbon emission efficiency between regions and city levels. According to the descriptive statistics in Table 6, the eastern region is significantly ahead of other regions in terms of the degree of digital economy development, and the central cities have a "first mover advantage" over the peripheral cities; There is also some variation in the mean values of

carbon emission efficiency between regions. The preceding conclusion lays the groundwork for testing the geographical heterogeneity of the digital economy and its impact on regional carbon emission efficiency.

Table 6. Regional digital economic development level and carbon emission efficiency.

	N	Mean	Std. Dev	Min	Max
			digital		
Northeastern	297	0.0407	0.0168	0.0124	0.108
Eastern	738	0.0727	0.0838	0.0117	0.714
Central	675	0.0398	0.0267	0.00913	0.348
Western	549	0.0410	0.0267	0.00936	0.229
Central Cities	288	0.122	0.117	0.0241	0.714
Peripheral Cities	1971	0.0406	0.0234	0.00913	0.272
			eff		
Northeastern	297	0.354	0.112	0.172	1.073
Eastern	738	0.489	0.182	0.234	1.230
Central	675	0.452	0.172	0.217	1.115
Western	549	0.466	0.220	0.176	1.375
Central Cities	288	0.434	0.189	0.176	1.202
Peripheral Cities	1971	0.458	0.186	0.172	1.375

Regression analysis of regional heterogeneity is performed in Figure 4. The regression results of line 1 to line 4 show that in the northeastern, eastern and central regions, the development of the digital economy plays a significant role in improving the carbon emission efficiency, especially in the eastern and central regions; the regression results are significantly positive at the 1% level. This suggests that the eastern region took initiatives in developing digital economy and has more obvious advantages in digital infrastructure and digital industry development, allowing them to play a greater role in digital empowerment with a variety of benefits, which is more important for carbon emission efficiency improvement. At the same time, the eastern region has a radiation-driven effect on the development of digital economy for the central region, benefiting from the digital technology spillover from the eastern region, the development pattern of the digital economy in the central region is further optimized, thus significantly contributing to the carbon efficiency of the central region. The northeastern region belongs to the traditional old industrial base area, along with the rapid development of the digital economy, the stimulating effect on the local traditional industrial sector may be more obvious, especially in promoting the digitalization of industrial industries. The northeastern region has been able to pay more attention to the use of low-carbon technologies in the process of industrial transformation and upgrading, which has greatly improved the efficiency of local carbon emissions. The digital economy development variables for the western region do not pass the significance test, most likely because the western region is still in the primary stage of digital economy development and the network infrastructure construction is still at a lagging level due to factors such as geographical location and factor accumulation. Lower resource utilization efficiency may be a significant factor as to why the digital dividend in the western area is not completely used.

The last two lines in Figure 4 indicate that the digital economy in central cities has a significant influence on improving carbon emission efficiency, whereas the development of the digital economy in peripheral cities has a significant inhibitory effect on regional carbon emission efficiency. This may be due to the fact that central cities have obvious advantages in the development process, exerting their siphon effect to gather various factors and forming basically perfect digital economy infrastructure, whereas peripheral cities are relatively backward in digital economy development and are still at the developing stage of

digital economy. Furthermore, the construction of digital economy infrastructure in cities generates more resource consumption, which reduces the efficacy of the infrastructure.

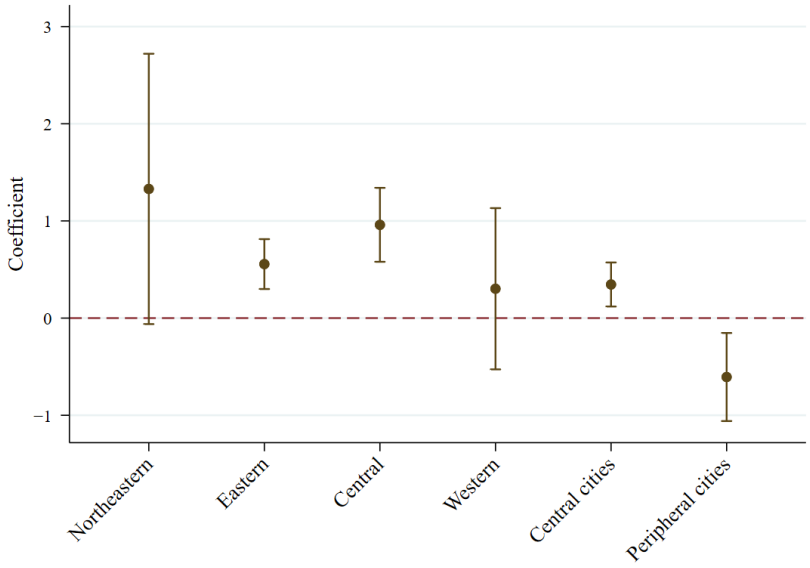


Figure 4. Regression results based on heterogeneity of sub-regional and city-level.

5. Discussion

Previous studies indicate a positive correlation between the digital economy and carbon emission efficiency, but the mechanisms by which the digital economy influences carbon emission efficiency still need to be further investigated. This section analyzes the transmission mechanism in greater detail to determine which factors can influence the digital economy and the carbon emission efficiency of the region.

5.1. Digital Economy, Energy Consumption and Carbon Emission Efficiency

In the previous chapters, we discussed possible mechanisms and pathways for the digital economy to influence carbon efficiency from the perspective of energy consumption. To verify this mechanism of action, we use energy consumption (Urban energy consumption mainly includes natural gas, liquefied petroleum gas and urban electricity. In this paper, the main urban energy consumption is converted into standard coal and then summed up to obtain urban energy consumption) as a mediating variable to test whether the digital economy has a further effect on carbon emission efficiency by influencing energy consumption. In Table 7, the results of Model 2 indicate that the coefficient of the digital economy is negative at the 1% level. This suggests that the development of the digital economy has a negative effect on energy consumption. It illustrates how the growth of the digital economy helps to utilize new energy sources and to enhance the efficiency of energy use to alleviate the problem of excessive energy consumption. The result of Model 3 shows that the coefficient of energy consumption is also significantly negative at the 1% level, whereas the coefficient of the digital economy is notably positive, which indicates that it has a favorable influence on carbon emission efficiency through optimizing the energy structure, confirmed by Hypothesis 2. This may be because the application of the digital economy in the energy sector accelerates the process of energy transition and improves the efficiency of energy production and utilization, which in turn reduces unnecessary energy consumption and improves the regional carbon emission efficiency.

Table 7. Intermediary effect regression results.

	Model 1 ***eff***	**Model 2** **ln*energy***	**Model 3** ***eff***
digital	0.591 ***	−2.391 ***	0.326 ***
	(0.0940)	(0.340)	(0.0873)
ln*erengy*			−0.110 ***
			(0.00568)
Control variables	YES	YES	YES
Constant	−0.983 ***	1.722 ***	−0.792 ***
	(0.174)	(0.628)	(0.160)
Observations	2259	2259	2259
Adjust R^2	0.277	0.706	0.392
Year	YES	YES	YES
City	YES	YES	YES

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels. The figures in () are t statistics.

5.2. Digital Economy, Industrial Value Chain and Carbon Efficiency

Although inter-industry upgrading promotes industrial value chain upgrading and further plays an important role in economic growth, it is equally important for improving carbon emission efficiency and promoting green development in China [64].

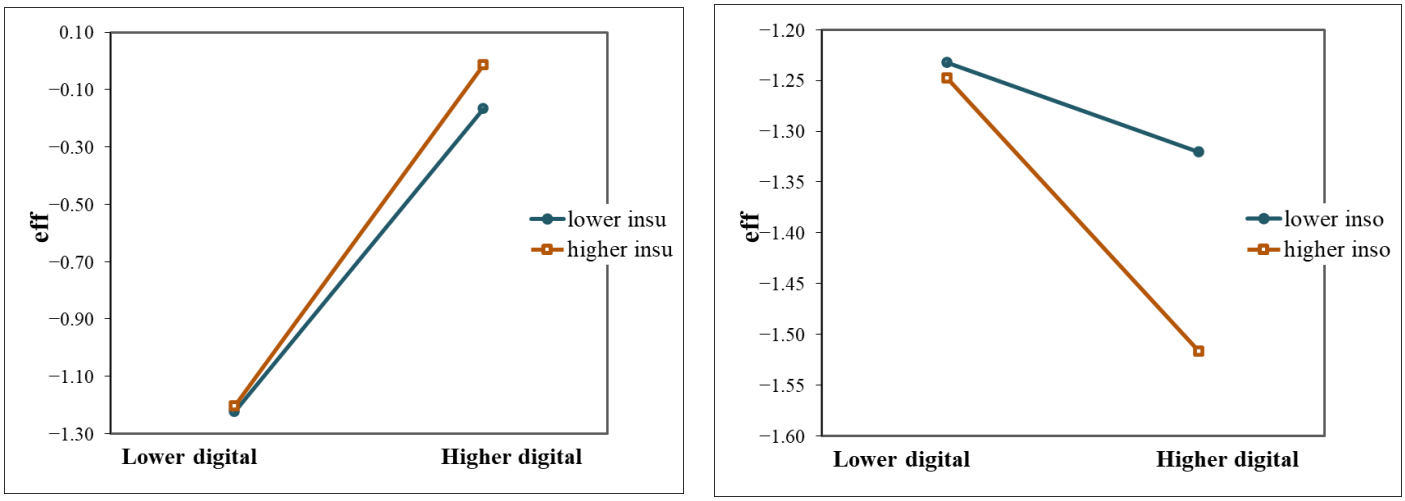
The transformation of industrial structure includes industrial structure upgrading (*isu*) (The upgrading of the industrial structure indicates the process of industrial structure's evolution and growth from a low level to a high level in accordance with the general rule of economic development.The research drawn from this part constructs the AIS index to calculate the advanced industrial structure by the cosine of the angle) and industrial structure rationalization (*iso*) (Industrial structure rationalization refers to the process of industrial restructuring and coordination. This paper draws on the practice of using the Theil index role to measure the degree of industrial structure rationalization), which are used as the moderating variables in the regression, respectively. The regression results are shown in Table 8. The result of model 2 indicates that the interaction term between industrial structure upgrading and digital economy is significantly positive at the 1% level, and industrial structure upgrading significantly enhances the influence of digital economy to promote carbon emission efficiency, which indicates that when industrial structure upgrading is at a high level, new industries with low energy consumption, low emission and high efficiency develop vigorously. Meanwhile, as the digital economy has grown, so has the need for digital management among local businesses, thereby creating good conditions for the region to use the digital economy to promote carbon efficiency. Thus, Hypothesis 3a is validated. The outcome of model 4 demonstrates, however, that the rationalization of industrial structure has a considerable weakening inhibitory impact in the process of promoting carbon emission efficiency by the digital economy, which confirms Hypothesis 3b. This indicates that the issue of adapting the development of the digital economy to the local industrial base and industrial structure is neglected in the process of promoting regional economic development, and the importance of the development of the digital economy is overemphasized, with more hotspot-oriented policy and other adjustments in the process of regional development. In fact, the rationalization of regional industries requires that the development of the digital economy must follow the objective laws of local economic and social development in order to achieve a reasonable allocation of production factors, which in turn can promote the coordinated development of various industries.

Table 8. Moderating effect regression results.

	Model 1 *eff*	**Model 2** *eff*	**Model 3** *eff*	**Model 4** *eff*
digital	0.595 ***	−1.025 ***	0.591 ***	−0.465 ***
	(0.0951)	(0.255)	(0.0941)	(0.173)
insu	0.00968	0.0370		
	(0.0276)	(0.0276)		
digital × *insu*		1.746 ***		
		(0.255)		
inso			−0.0147	−0.0559 **
			(0.0245)	(0.0249)
digital × *inso*				−4.316 ***
				(0.596)
Control	YES	YES	YES	YES
Constant	−1.039 ***	−1.420 ***	−0.969 ***	−1.230 ***
	(0.236)	(0.240)	(0.175)	(0.177)
Observations	2259	2259	2259	2259
Adjust R^2	0.277	0.294	0.277	0.296
Year	YES	YES	YES	YES
City	YES	YES	YES	YES

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels. The figures in () are t statistics.

Further, we analyze the relationship between the digital economy and carbon emission efficiency at the level of industrial structure upgrading and the level of industrial structure rationalization above or below the median. The results of Figure 5a indicate that the development of the digital economy has a significant effect on carbon emission efficiency in both high and low industrial structure upgrading. On the contrary, Figure 5b shows that the growth of the digital economy has a negative effect on carbon emission efficiency in both high and low industrial structure rationalization. This effect is particularly pronounced when the industrial structure rationalization at a high level.



(**a**) (**b**)

Figure 5. Moderating effect of industrial transformation. (**a**) Industrial structure upgrading; (**b**) Industrial structure rationalization.

6. Conclusions and Policy Implication

Based on the panel data of Chinese prefecture-level cities from 2011–2019, the carbon emission reduction mechanism and influence on the digital economy are empirically tested in several dimensions based on the construction of the digital economy development level index. The key findings are as follows: First, the digital economy significantly

improves carbon emission efficiency, and the conclusions are still valid when endogeneity and a series of robustness variables are taken into account; Second, the effect of digital economy on carbon emission efficiency is regionally heterogeneous, with greater promotion effects in the eastern and central regions. The digital economy in central cities also has a significant effect on carbon emission efficiency, whereas peripheral cities on the contrary have a significant inhibitory effect; Third, the mechanism analysis shows that the digital economy can help improve the efficiency of urban carbon emissions by improving energy consumption as a pathway; Fourth, the industrial value chain has a moderating effect on the impact of digital economy on carbon emission efficiency, among which, industrial structure upgrading can significantly enhance the impact of digital economy on carbon emission efficiency enhancement, although it has a significant weakening and inhibiting effect in the process of digital economy promoting carbon emission efficiency enhancement. The main contribution of this paper is to provide more theoretical and empirical support for the influence of the digital economy on carbon emission efficiency. Nonetheless, there is potential for development in this paper, mostly owing to the availability of data. The assessment index system for the growth of the digital economy in cities is insufficiently thorough, so the index system presented in this study may also be inadequately extensive. Future enhancements of the established indicator system are contingent upon technological feasibility and data availability.

Based on the preceding facts, we conclude the following policy implications.

First, the digital economy is progressively becoming a significant driver of economic growth, and the findings of this paper imply that the expansion of the digital economy is also favorable to the accomplishment of the carbon peak carbon neutrality aim. Therefore, local governments should accelerate the growth of the digital economy and maximize the dividend impact of the digital economy on reducing carbon emissions efficiently. By constructing a high-speed, green and low-carbon, secure and controllable, intelligent and comprehensive digital information infrastructure, the government should accelerate the application of digital economy in social life, especially in the environmental field, how to guide the transformation and upgrading of traditional industries, and rely on digital technologies such as 5G, big data, and artificial intelligence to promote industrial innovation and pollution emission reduction, and foster the emergence of new technologies, industries, and business models related to low-carbon fields. Governments should leverage their scale impact and technology effect to transform the digital economy into a sustainable force that promotes carbon emission efficiency.

Second, the application of the internet in the energy industry should be enhanced and its integration with energy production and consumption should be encouraged. In the context of developing the digital economy, the government should guide the transformation and upgrading of high energy-consuming industries, especially by putting the digital economy technology represented by the Internet into the development and transformation of traditional manufacturing industries, encouraging the intelligent upgrading of energy production, transportation, consumption and other aspects, realizing the upgrading and optimization of industrial structure, promoting the deep integration of the Internet and the real economy, and pushing the further transformation of the manufacturing industry from traditional manufacturing to intelligent manufacturing. Promoting the low-carbon transformation of the energy sector can make full use of the urbanization process, apply the digital economy to the process, realize the adjustment and optimization of the energy structure, and promote the level of green ecological environment in cities.

Finally, digitalization can be used to promote regional green and coordinated development and reduce regional disparities. The digital economy gradually integrates local economic activities into regional production networks, leading to changes in regional production and industrial organization, and has become a significant vehicle for promoting urban and economic transformation. Although digitalization consolidates the advantages of digital economy development in eastern and central regions as well as in central cities, it also gradually promotes the transfer of digital economy technology inputs and applications

to less developed regions, so that less developed regions can also receive technological dividends, achieve effective growth in economic efficiency in the region, and gradually reduce the overall gap with developed regions. At the same time, we should strengthen inter-regional cooperation, create an integrated digital economy intelligent service platform, establish a large digital economy service repository, realize data and technology resource sharing, use digital technology to enhance urbanization and digital governance in each region, and promote the development of the low-carbon economy.

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