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Original Research

The Effects of Digitization and Environmental Regulation on Energy Consumption in China

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Abstract

The optimization of energy consumption structure and the mitigation of carbon emissions are crucial for developing countries to achieve high-quality economic development and green transformation. Utilizing prefecture-level panel data, this study investigates the impact of environmental regulation on energy consumption and carbon emissions in China within the framework of digitization. The findings indicate that interacted effects of digitization and environmental regulation result in a significant reduction in high-carbon energy consumption and associated carbon emissions. Besides, as digitization progresses, higher levels of environmental regulation can enhance the positive effects of digitization on low-carbon energy consumption and its carbon emissions. Mechanism analyses suggest that digitization development, coinciding with environmental regulation, plays a vital role in regulating energy consumption in high-carbon and low-carbon energy sectors by fostering investment in energy equipment. The impact of interactions on clean energy consumption shows a double threshold effect of both digital development and environmental regulation. However, an excessively high scale of digitization beyond the second threshold is also found to reduce clean energy consumption.

Keywords: Digitization, environmental regulation, clean-energy consumption, energy equipment investment, low-carbon

Introduction

The global goal of achieving carbon emission reductions in response to climate change has continued to encounter numerous challenges. Establishing a favorable ecological environment and promoting green and low-carbon production paths are the most important foundations for developing countries to adhere to sustainable and high-quality development. Taking China, the largest developing country, as an example, the China Greenhouse Gas Bulletin 2022 reports that global and Chinese atmospheric carbon dioxide concentrations reached 413.2 ppm and 414.3 ppm in 2020, representing the highest values observed in China since 1990. China's journey towards green and low-carbon development has gained momentum, marked by a series of measures and concerted efforts to facilitate a comprehensive green transformation of economic and social development. The "14th Five-Year Plan" signifies a critical and opportune period for achieving carbon peaks. It is imperative to firmly anchor the key strategic direction of carbon reduction and enhance the synergy between

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climate change response and environmental governance. Official data indicates that China's energy sector contributes to half of the country's total greenhouse gas emissions. Adjusting the energy structure constitutes an effective way to reduce pollutant emissions, including carbon, at the source. It is worthwhile for academics to further explore how to realize the dual-carbon goal, starting from energy consumption.

Simultaneously, digitalization development has emerged as a pivotal focal point in economic strategy. In 2020, the scale of China's digitization reached 39.2 trillion yuan, constituting 38.6% of the GDP. The "14th Five-Year Plan" for the Development of Digitization proposes that by 2025, the added value of the core industries within the digitization will represent 10% of the GDP. The participation of digital technology in economic activities breaks the traditional high energy-consuming and high-polluting mode of economic growth, effectively reflecting the concept of green development. This coincides with the concept of eco-efficiency in which less cost is used to create greater output and fewer natural resources are used to create greater economic benefits.

With the deepening development of digitization, integrating it with low-carbon goals has made it possible to use digital pathways to achieve green transformation and low-carbon energy consumption. Environmental regulation is often used as one of the government's tools to regulate and control regional ecosystems and pollution emissions. In the context of the deepening digitization integration and energy transition, analyzing the interacted impacts of environmental regulation on energy consumption is particularly critical in achieving high-quality development and green transition. What are the moderating and coupling effects of combining environmental regulatory policy instruments with digitization development on energy consumption structure and its carbon emission? What are the mechanisms involved?

Extensive studies have examined the determinants of energy consumption and carbon emissions, focusing on macro policies and industrial agglomeration. For instance, the increased industrial agglomeration possesses significant spatial spillover capacity, breaking the high-carbon lock-in effect of coal [1]. Literature has examined the effect of digitization development on energy consumption and carbon emissions. Digitization development amplifies the energy consumption scale by economic growth, energy efficiency, and industrial structure [2]. Notably, digitization introduces spatial spillover effects on urban energy efficiency [3] and carbon emissions [2]. Studies highlight that digital technology enhances carbon emission performance through factors like energy intensity, energy consumption scale, urban afforestation, industrial structure, and green economy efficiency [4-6]. However, scholars have not yet reached a unified conclusion on the effect of digitization on carbon emissions. Multiple studies indicate an inverted U-shaped nonlinear characteristic in the relationship between digitization and carbon emissions [7-9]. For example, the digital economy can indirectly curb carbon emissions by economic agglomeration [7]. Similar to the digital economy, digital finance can increase energy-environmental performance by pure technical efficiency and promote green development in China [10, 11].

On the other hand, scholars argue that while environmental regulation drives green technological innovation, the associated costs in production deter investment in R&D and hinder green innovation efforts [12, 13]. The relationship between environmental regulation and total factor energy efficiency is characterized as non-linear [14]. In addition, the impacts of different environmental regulation policy tools on firm energy-environment efficiency and green technological innovation are heterogeneous [15]. With every 1% increase in a command-and-control and market-based incentive policy, energy-environment efficiency increases by 0.01-0.02%, while the effect of public participation policy tools is not significant [16].

Recent studies indicate that the effectiveness of carbon emission reduction is influenced by environmental regulations [17]. Nevertheless, some research has concluded that environmental regulations lead to an increase in carbon emissions within the context of market segmentation [18]. Existing literature on environmental regulations and energy consumption, as well as carbon emissions, primarily delves into the "green paradox" effect, the "reverse emission reduction" effect, and the non-linear threshold effect [19, 20]. The prevailing inclination is toward supporting the notion that environmental regulations play a heterogeneous role at different threshold stages [21]. The mechanism of the environmental regulation's effect on carbon emissions is complex, requiring further analysis across different industries and regulatory intensities to uncover potential non-linear and threshold effects. For instance, digital countryside initiatives have shown promise in achieving carbon emission reduction in agriculture [22]. However, significant variations in carbon emission reduction effects are observed concerning environmental regulation intensity, with more pronounced effects in areas with medium environmental regulations [13]. Informal environmental regulation has a greater impact on regional carbon emission reductions by improved structural transformation of industries and renewable energy substitution [23]. Besides, government-imposed market-based regulations positively enhance the economic benefits derived from corporate environmental performance [24].

Some studies have also concentrated on the interactive effects of digitization and environmental regulation. Digitization is a key pathway for environmental regulation to enhance high-quality economic development, and strengthening the integration between digital platforms and environmental regulation could benefit economic progress [25]. With the progressive reinforcement of environmental regulation, digitization assumes a pivotal role in fostering technological innovation and public participation [26]. Simultaneously, there is a noticeable increase in the willingness to engage in environmental governance, with the Internet and digital technology recognized as pivotal channels for promoting public governance [27]. Regarding energy efficiency, scholars have noted that the digitization follows the Environmental Kuznets Curve, indicating its potential to enhance energy consumption structure with a threshold effect. Environmental supervision plays a mediating role in the relationship between digitization and the upgrading of energy consumption structure [28, 29]. Some scholars have pointed out that environmental regulations can also undermine the positive effects of the digital economy on green development [30].

In summary, researchers have conducted comprehensive studies on digitalization, environmental regulation, and carbon emissions. However, few studies have integrated these elements into a coherent analytical framework, focusing on their interactions with carbon emissions from energy consumption particularly. Rare studies have systematically explored the mechanisms by which digitalization and environmental regulation interact on energy consumption. In addition, the mechanisms of energy consumption emission reduction affected by digitization remain under-explored. Addressing these issues can help to promote green technological innovation and foster high-quality economic development in developing countries. Therefore, this paper aims to reveal how environmental regulation affects energy consumption and its carbon emission effects in the context of digitalization development. The findings contribute to driving investment in green and low-carbon areas and to forming a new growth point of economic and social development.

Compared with previous studies, the marginal contributions are (1) it adds to the literature on energy consumption determinants by examining how digital development and environmental regulation influence energy consumption and carbon emissions, using city-level panel data; (2) it offers a detailed analysis of the non-linear effects of energy consumption, investigating potential threshold effects of digitalization trends and environmental regulation on energy consumption. The study also lays the foundation for developing countries to formulate targeted environmental regulatory policies to promote digitalization. The subsequent sections are organized as follows. The second section outlines the theoretical hypotheses and the adopted research methodology. Empirical model estimation results and analyses are expounded upon in the third section. The paper concludes with pertinent policy recommendations.

Materials and Methods

Materials of Theoretical Mechanisms

Integrating digitization with the Internet enhances collaboration in technological innovation and research, optimizes energy structures by improving resource allocation, reduces industrial management and transaction costs, x`and mitigates high-carbon consumption [4, 29]. Digital technology, utilizing aggregated data for accurate predictions of inputs and outputs, transforms traditional high-input, high-consumption production models and establishes a scientific monitoring system. This fosters comprehensive energy use by reducing high-carbon energy consumption and increasing low-carbon and clean-energy usage, alongside carbon emissions, through optimized energy equipment investments. However, digital technology, reliant on energy-intensive infrastructure like cloud, blockchain, and data centers, also demands significant electricity for development and operation [31].

The growth in energy consumption affected by digitization has two aspects: direct energy use in tech production, use, and disposal, and indirect demand from economic development fueled by digital technology. Without achieving green technology innovation and energy substitution, digital technology might exacerbate the deterioration of the energy consumption structure and the rebound effect of carbon emissions influenced by environmental regulation. Recent findings suggest a U-shaped relationship between digital technologies and energy consumption efficiency. The stronger the environmental regulation on the right side of the inflection point, the greater the role of digitization in promoting energy efficiency [27]. Additionally, environmental regulation has not yet crossed Potter's inflection point and continues to have a dampening effect on green development efficiency [32].

Environmental regulation is intrinsically linked to the Internet economy behind digitization, forming a closely connected and complementary relationship. Literature suggests that the impact of environmental regulation on green technological innovation generally follows a "U" shape, and digitization positively influences green technological innovation, reducing the inflection point of environmental regulation intensity [28]. Coordination between digitization and environmental regulation may be instrumental in promoting a low-carbon economy and high-quality development [7, 25]. Therefore, this paper proposes the following hypotheses:

Hypothesis 1: The interaction between digitization and environmental regulation can optimize the energy consumption structure and reduce carbon emissions from energy consumption.

Hypothesis 2: The impact of environmental regulation on energy consumption structure is subject to a threshold effect depending on both digitization and environmental regulation.

Methods

Econometric Model

The paper aims to analyze how digitization and environmental regulation interact to affect energy consumption and carbon emissions, using city-level data from 2011 to 2019 in China. The econometric model is set in Equation (1) as follows:

$$EConsum_{it} = \alpha_0 + \beta_1 ER_{it} \times Digital_{it} + \beta_2 ER_{it} + \beta_3 Digital_{it} + \beta_4 X_{it} + \gamma_j + \sigma_t + \varepsilon_t \quad (1)$$

Where i and t are subscripts representing individual and year, respectively. The dependent variable, denoted as energy consumption ($EConsum_{it}$), is measured by the energy consumption source and energy carbon emissions. In consideration of the moderating effect of environmental regulation, the core independent variable is the interaction term between environmental regulation (ER_{it}) and digitization development ($Digital_{it}$), introduced based on the equation (1). Vector X encompasses the control variables, including the foreign investment used (*FDI*), population density (*Pop*), fixed asset investment (*Asset*), the number of industrial enterprises (*Industrial_enter*), economic development (*GDP*), and the amount of industrial soot removed (*Smokemove*), which collectively impact energy consumption. The model incorporates city-fixed effects (γ_j) and time-fixed effects (σ_t), with ε_t representing the residual term. To examine the mechanism behind the moderating effect, the paper substitutes the dependent variable in equation (1) with the investment in various energy equipment. Enterprises can increase their pollution control investments and purchase energy equipment for pollution control purposes [16]. The main interest coefficient is β_1.

To further investigate the non-linear effects of digitization development and environmental regulation on energy consumption, both digitization development and environmental regulation are adopted as threshold values, respectively. This paper constructs the following double threshold model in Equations (2)-(3):

$$EConsum_{it} = \alpha_0 + \beta_1 ER_{it}(ER_{it} < \theta_1) \times Digital_{it} + \beta_2 ER_{it}(\theta_1 < ER_{it} < \theta_2) \times Digital_{it} + \beta_3 ER_{it}(ER_{it} > \theta_2) \times Digital_{it} + \beta_4 X_{it} + \gamma_j + \sigma_t + \varepsilon_t \quad (2)$$

$$EConsum_{it} = \alpha_0 + \beta_1 ER_{it} \times Digital_{it}(Digital_{it} < \theta_1) + \beta_2 ER_{it} \times Digital_{it}(\theta_1 < Digital_{it} < \theta_2) + \beta_3 ER_{it} \times Digital_{it}(Digital_{it} > \theta_2) + \beta_4 X_{it} + \gamma_j + \sigma_t + \varepsilon_t \quad (3)$$

Where ER_{it} and $Digital_{it}$ are the threshold variables of environmental regulation and digitization, respectively. Coefficients of θ_1 and θ_2 denote the threshold estimates, which take the value of 1 if the conditions in parentheses are met, and 0 if they are not. The rest variables are defined as Equation (1).

Variable Definitions

1. Independent variables

Digitization development relies on an index system that combines Internet digitization and digital finance. This study employs the entropy value method and principal component analysis to construct urban-level data, drawing on the work of Wang et al. [7] and Ma et al. [28]. Specifically, the Internet penetration rate is measured by the number of Internet broadband access users per 100 people. The relevant Internet practitioners are quantified by the proportion of employees in the computer services and software industry in urban units. The relevant Internet outputs are determined by the total amount of telecommunication services per capita. The penetration rate of cell phones is measured by the number of cell phone subscribers per 100 people. The index of digital financial inclusion serves as a measure of digital finance level. These factors are standardized and dimensionality reduced to obtain the digitization index.

While existing literature often uses pollution emissions as a proxy for environmental regulation, this indicator may face endogeneity problems like reverse causation. This paper, considering data availability, measures environmental regulation from the perspective of regulatory policies. Following Wang and Zhang [33], the frequency of words related to "environment" and "environmental protection" in the annual working reports issued by prefecture-level municipal governments is counted. The percentage of these words in the full text of the government's working reports is calculated as a proxy for environmental regulation.

2. Dependent Variables

The dependent variables are categorized into high-carbon energy consumption (*HC_consum*), low-carbon energy consumption (*LC_consum*), and clean energy consumption (*CC_consum*) based on energy consumption characteristics. Referring to existing literature [34], natural gas consumption represents low-carbon energy, coal energy consumption stands for high-carbon energy, and electricity consumption is denoted as clean energy. The proportions of low-carbon energy and high-carbon energy to the total energy consumption are measured as *HC_rate* and *LC_rate*, respectively. The carbon emission index of energy consumption is determined by the carbon dioxide emissions generated from the consumption of high-carbon energy (*HC_carbon*), low-carbon energy (*LC_carbon*), and clean energy (*CC_carbon*) at the city level.

3. Instrumental Variables (IVs)

Digitization can affect the regional energy consumption structure and its carbon emissions by technological innovation and industrial optimization and upgrading. Conversely, cities with relatively high energy consumption structure and carbon emissions may create a favorable environment for digitization, leading to interdependent endogeneity problems [2]. Additionally, other unobservable factors may impact regional energy consumption. To address endogeneity problems, this study adopts the instrumental variable method and the lagged variable of digitization development to conduct dynamic panel regressions. As digitization is rooted in the application of Internet technology, and the widespread use of the Internet began with fixed-line telephones, the instrumental variable is constructed as the interaction term between the number of fixed-line telephones per 100 people in each province in 1984 and the amount of national Internet investment in the previous year.

Data

The sample data spanning 2011-2019 are from the China Statistical Yearbooks, China Urban Statistical Yearbooks, China Environmental Statistical Yearbooks, statistical annual reports of some prefectural-level cities, government work reports, etc. The data of digital financial inclusion for the same period are sourced from the Peking University Digital Financial Inclusion Index (2011-2020). Nominal variables in the sample have been deflated using 2010 price indices, and some missing values have been addressed by interpolation.

Results and Discussion

Basic Results

Table 1 presents the results regarding the interaction between digitization and environmental regulation on energy consumption. In columns (1)-(3), it is evident that both digitization and environmental regulation play crucial roles in determining energy consumption. Digitization notably decreases the consumption of high-carbon energy while increasing the consumption of low-carbon energy and clean energy. Conversely, environmental regulation exhibits a negative impact on the consumption of high-carbon and clean energy. The results in columns (4)-(6) demonstrate that with the advancement of digitization, stronger urban environmental regulation significantly reduces high-carbon energy consumption and increases low-carbon energy consumption. Yin et al. also noted that low-carbon policies could reinforce the inverted U-shaped effect between the digital economy and carbon intensity and move the inflection point [35]. The coefficients of environmental regulation in columns (2) and (6) are not significant, probably because the effects of environmental regulation on low-carbon energy and clean energy consumption need to consider the role of digitization development. The subsequent analysis in Table 4 illustrates the existence of a double threshold of digitization development on low-carbon energy consumption. Affected by digitization development and environmental regulation, the interaction term in column (6) has a non-significant effect on clean energy consumption. This may be due to the non-linear threshold effects of the interaction term between digital development and environmental regulation on clean energy consumption (see Table 4). Besides, different types of environmental regulation may have heterogeneous impacts on energy consumption [16]. For example, market-based environmental regulations exhibit a significantly positive moderating effect on the correlation between energy endowment and energy efficiency, while this effect is found to be insignificant for command-and-control environmental regulations [33].

Columns (7)-(16) report regression results using instrumental variable (IV) methods. An interaction term between the number of fixed-line telephones per 100 people in each province in 1984 and the amount of national Internet investment in the previous year is used as an instrumental variable in columns (7)-(11). The results show that there is an endogeneity problem, and it can also reject the under-identification test of IVs at the 5% significance level, but it does not pass the weak identification test of the IV. Using lagged variables of digitization development in columns (12)-(16), these regressions conduct under-identification tests and weak identification tests[1], proving the reliability of the results. Those estimated coefficients indicate that urban environmental regulations, coupled with digitization, effectively reduce both the quantity and proportion of high-carbon energy consumption. Besides, as digitization progresses, higher levels of environmental regulation can enhance the positive effects of digitization on low-carbon energy consumption. Xie et al. conclude that the digital economy enhances inclusive green growth, while environmental regulation undermines the benefits of inclusive green growth characterized by spatial spillovers [30].

Analysis of Carbon Emissions from Energy Consumption

The total carbon dioxide emissions resulting from high carbon, low carbon, and clean energy consumption in each city are calculated using the energy consumption quantity and carbon emission coefficient method in the paper. These values are then added as dependent variables in the regressions. Table 2 illustrates the impact of environmental regulation on carbon emissions from energy consumption affected by digitization.

In columns (1)-(3), the estimated coefficients for carbon emissions from energy consumption are reported separately for digitization and environmental regulation. The coefficients reveal that carbon emissions from

[1] The p-value of Anderson LM statistic is less than 0.01, implying that the hypothesis of "under-identification of IV" is significantly rejected at 1% level. The value of Cragg-Donald Wald F is 289.245 which is greater than the 10% threshold value of 16.38 in Stock-Yogo weak ID test critical values, passing weak identification tests of IVs. There is only one IV that does not have overidentification issues.

Table 1. Estimated results of digitization, environmental regulation on energy consumption.

Interacted effects	(1)	(2)	(3)	(4)	(5)	(6)
	HC_consum	LC_consum	CC_consum	HC_consum	LC_consum	CC_consum
Digital*ER	-	-	-	139.705**	1.040*	-0.196
	-	-	-	(61.498)	(0.567)	(0.787)
Digital	-0.663***	0.007***	0.007***	-1.085***	0.003	0.008**
	(0.173)	(0.002)	(0.002)	(0.254)	(0.002)	(0.003)
ER	-9.455***	-0.032	-0.153***	-22.556***	-0.130**	-0.135
	(3.518)	(0.032)	(0.045)	(6.753)	(0.062)	(0.086)
FDI	-0.001	0.000***	0.000**	-0.001	0.000***	0.000**
	(0.002)	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)
Pop	-0.016	0.001***	0.002***	-0.009	0.001***	0.002***
	(0.023)	(0.000)	(0.000)	(0.023)	(0.000)	(0.000)
Asset	-0.325***	0.008***	0.006***	-0.330***	0.008***	0.006***
	(0.078)	(0.001)	(0.001)	(0.078)	(0.001)	(0.001)
Industrial_enter	-103.110	-6.391***	-1.793	-63.525	-6.097***	-1.849
	(158.065)	(1.456)	(2.020)	(158.880)	(1.464)	(2.033)
GDP	-0.079	0.005***	0.008***	-0.080	0.005***	0.008***
	(0.114)	(0.001)	(0.001)	(0.114)	(0.001)	(0.001)
Smokemove	0.005***	0.000***	0.000***	0.005***	0.000***	0.000***
	(0.002)	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
N	2583	2583	2583	2583	2583	2583
R^2	0.066	0.590	0.675	0.068	0.591	0.675

IV regressions	(7)	(8)	(9)	(10)	(11)
	HC_consum	LC_consum	CC_consum	HC_ rate	LC_rate
Digital*ER	13037.386**	-77.235**	-68.471**	774.406**	3.305
	(5864.505)	(36.257)	(33.106)	(378.183)	(8.446)
Digital	-73.533**	0.443**	0.391**	-4.468**	-0.004
	(32.918)	(0.204)	(0.186)	(2.123)	(0.047)
ER	-1290.300**	7.556**	6.552**	-75.054**	-0.259
	(575.679)	(3.559)	(3.250)	(37.124)	(0.829)
Control variables	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes
Province fixed effect	Yes	Yes	Yes	Yes	Yes
N	2583	2583	2583	2583	2583
Lagged variable regressions	(12)	(13)	(14)	(15)	(16)
	HC_consum	LC_consum	CC_consum	HC_ rate	LC_rate

Table 1. Estimated results of digitization, environmental regulation on energy consumption.

L.Digital*ER	27.125*	0.972**	0.466	-10.011*	2.002***
	(13.720)	(0.435)	(0.582)	(5.769)	(0.409)
L.Digital	-2.156***	0.015***	0.028***	-0.050	0.001
	(0.511)	(0.005)	(0.007)	(0.065)	(0.005)
ER	-14.056**	-0.084	-0.123*	1.633**	-0.128***
	(5.553)	(0.053)	(0.071)	(0.701)	(0.050)
Control variables	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes
Province fixed effect	Yes	Yes	Yes	Yes	Yes
N	2296	2296	2296	2296	2296

Note: * Significant at 10% level; ** significant at 5% level; *** significant at 1% level. Standard errors are in parentheses.

Table 2. Effects of Digitization and Environmental Regulation on Carbon Emissions of Energy Consumption.

IV method	(1)	(2)	(3)	(4)	(5)	(6)
	HC_carbon	LC_carbon	CC_carbon	HC_carbon	LC_carbon	CC_carbon
Digital*ER	-	-	-	0.043**	0.002*	-0.139
	-	-	-	(0.019)	(0.001)	(0.560)
Digital	-0.000***	0.000***	0.005***	-0.000***	0.000	0.005**
	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.002)
ER	-0.003***	-0.000	-0.109***	-0.007***	-0.000**	-0.096
	(0.001)	(0.000)	(0.032)	(0.002)	(0.000)	(0.062)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
N	2583	2583	2583	2583	2583	2583

Note: * Significant at 10% level; ** significant at 5% level; *** significant at 1% level. Standard errors are in parentheses.

high-carbon energy consumption affected by digitization are significantly negative, while carbon emissions from low-carbon and clean energy consumption are significantly positive. The impact of environmental regulation on carbon emissions from high-carbon and clean energy consumption is both negative and significant. Robust environmental regulation can serve as a guarantee for the efficient operation of carbon emission reduction efforts [17].

Moving to columns (4)-(6), interaction terms between digitization and environmental regulation are introduced. With higher digitization development and stronger environmental regulation, there is a more significant reduction in carbon emissions generated by high-carbon energy consumption and an increase in carbon emissions generated by low-carbon energy consumption. Some studies have concluded that the moderating effect of environmental regulation significantly enhances the efficiency of the marine green economy and promotes its efficiency in neighboring regions through positive spatial spillover effects [36]. Although digitization exhibits a positive promoting effect on carbon emissions in column (3), this interacted impact of digitization and environmental regulation on carbon emission of clean energy consumption is nonsignificant, as shown in column (6).

Mechanisms Analysis

The estimated results of digitization development and environmental regulation effects on city investment in energy equipment are presented in Table 3.

The estimated coefficients of interaction terms in column (1) and column (4) reveal that their interacted effects on investment in total energy equipment and clean energy equipment are insignificant. In column (2), it is observed that the contribution of digitization development to investment in high-carbon energy equipment decreases as the level of environmental regulation rises. The coefficients in column (3) further indicate that the positive impact of digital development on low-carbon energy equipment investment is strengthened with higher levels of environmental regulation.

Investment in energy equipment is positively correlated with energy demand [37]. Wang et al. noted that the early-stage substitution and upgrade of energy equipment significantly affect carbon energy consumption [7]. The investments in high-carbon and low-carbon energy equipment serve as a motivating factor for firms to optimize energy production and enhance energy efficiency, consequently increasing high-carbon and low-carbon energy consumption. These findings suggest that digitization and environmental regulation play a regulatory role in high-carbon and low-carbon energy consumption and their associated carbon emissions by adjusting investment in high-carbon energy and low-carbon energy equipment.

Threshold Effect Results

The analyses provide substantial evidence supporting the moderating effect of environmental regulation and digitization on energy consumption and its carbon emissions. To investigate potential threshold effects, this paper examines the non-linear impact of environmental regulation on low-carbon consumption, taking into account the digitization development. Both utilizing digitization development and environmental regulation as threshold variables, the bootstrap method is employed for sequential testing to identify non-linear trends.

Table 4 presents the results of the single threshold and double threshold effects of digitization and environmental regulation on energy consumption since there is no triple threshold tested. When using environmental regulation as a threshold variable, the F-statistic coefficient shows no single or double threshold non-linear effect of the interaction between digitization and environmental regulation on high-carbon and low-carbon energy consumption. Zhang et al. [38] found no significant threshold effect of environmental regulations on CO_2 emissions. The interaction terms in Table 1 are not significant on clean energy consumption, while Table 4 yields a non-linear effect of digital development and environmental regulation on clean energy consumption with a double threshold for environmental regulation. This result implies that the interacted effect positively boosts clean energy consumption after crossing the environmental regulation threshold. This may be explained by the fact that environmental regulation and green investment that are associated with energy consumption are non-linearly related [13].

In contrast, regarding digitization development as a threshold variable, the results reveal a double threshold nonlinear effect of the interaction between digitization and environmental regulation on low-carbon and clean energy consumption. This suggests that with the strengthening of environmental regulation, higher digitization development led to a more significant increase in low-carbon and clean energy consumption. However, this positive effect on low-carbon energy consumption first increases and then decreases. An excessively high level of digitization development

Table 3. Effects of Digitization and Environmental Regulation on Energy Equipment Investment.

	(1)	(2)	(3)	(4)
	TE_invest	HC_invest	LC_invest	CC_invest
Digital*ER	-6.352	-4.795*	3.021**	4.911
	(11.036)	(2.898)	(1.285)	(7.933)
Digital	-0.001	0.033***	-0.017***	-0.063*
	(0.046)	(0.012)	(0.005)	(0.033)
ER	0.663	1.123***	-0.131	-0.844
	(1.212)	(0.318)	(0.141)	(0.871)
Control variables	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes
Province fixed effect	Yes	Yes	Yes	Yes
N	2583	2583	2583	2583

Note: * Significant at 10% level; ** significant at 5% level; *** significant at 1% level. Standard errors are in parentheses.

Table 4. Threshold Effects of Digitization and Environmental Regulation on Energy Consumption.

	Threshold : ER			Threshold : Digitization		
	HC_consum	LC_consum	CC_consum	HC_consum	LC_consum	CC_consum
Digital*ER (dumm = 0)	544.106***	461.203	1.925***	0.358	0.992	-2.554*
Digital*ER (dumm = 1)	267.086***	-59.636	-1.271	2.299***	-3.420***	1.442
Digital*ER (dumm = 2)	202.432***	67.361	1.677***	-1.171	0.796	-2.439***
Threshold 1	0.0018	0.0908	0.0024	0.1893	0.0024	0.0908
Threshold 2	0.0042	0.0932	0.0039	-	0.0039	0.1893
F *statistics* -single	5.57	16.08	11.49	68.59***	14.03*	101.88***
critical value 10%	15.148	18.887	13.325	29.031	13.792	21.263
critical value 5%	19.243	23.112	17.751	34.528	17.757	25.233
critical value 1%	29.327	32.418	21.114	45.563	21.024	41.142
F *statistics* -double	4.75	4.03	32.89***	39.31	25.57***	59.90***
critical value 10%	11.761	16.875	12.899	74.395	12.105	17.001
critical value 5%	13.778	20.152	14.708	95.298	14.086	21.502
critical value 1%	19.870	25.163	18.752	116.055	19.239	26.015
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.037	0.040	0.523	0.534	0.569	0.588
N	2583	2583	2583	2583	2583	2583

Note: * Significant at 10% level; ** significant at 5% level; *** significant at 1% level. Standard errors are in parentheses.

significantly reduces clean energy consumption after crossing the second threshold. Studies also used digital financial inclusion as a threshold variable to reveal that environmental regulation in both eastern and western regions exerts a single threshold effect on economic development [39]. To validate whether the estimated threshold value equals its true value, likelihood ratio statistics and likelihood ratio graphs are employed to obtain effective threshold estimates for low-carbon energy consumption and clean energy consumption[2].

Conclusions

Based on city-level panel data, this paper provides a thorough analysis of how digitization and environmental regulation interact to affect energy consumption and carbon emissions. The key findings and policy implications are outlined below.

The study reveals that digitization development is associated with a positive contribution to low-carbon consumption. In contrast, environmental regulation discourages both high-carbon and clean-energy consumption, but does not affect low-carbon energy consumption. The interacted effects of digitization and environmental regulation result in a significant reduction in high-carbon energy consumption and associated carbon emissions. Besides, as digitization progresses, higher levels of environmental regulation can enhance the positive effects of digitization on low-carbon energy consumption and Its carbon emissions. Mechanism analyses suggest that digitization development, coinciding with environmental regulation, plays a vital role in regulating energy consumption in high-carbon and low-carbon energy sectors by fostering investment in energy equipment.

In terms of threshold effects analysis, a non-linear effect of digitization and environmental regulation on clean energy consumption with a double threshold for environmental regulation is identified. The results also reveal a double threshold of digitization development in the interacted effects between digitization and environmental regulation on low-carbon and clean energy consumption. The middle and low-level scales of digitization, affected by environmental regulation, show

[2] The likelihood ratio graphs are not shown, which are available upon request.

an inverted U-trend, significantly increasing low-carbon and clean energy consumption. However, an excessively high scale of digitization beyond the second threshold is also found to reduce clean energy consumption.

The paper's policy implications are multifaceted. First, governments are encouraged to design top-level optimization plans for digitization and environmental regulations, emphasizing the low-carbon utility of digitization. Additionally, efforts to control carbon emissions should involve optimizing capital allocation in the energy industry, with a focus on low-carbon and clean-energy investments. Differentiated policies for digitization development are recommended, considering local conditions, digital development scale, environmental regulation, and energy consumption characteristics in each area. Regions with advanced digital economy development that exceed threshold values should prioritize structural and quality improvements and enhance carbon tax and emission market systems. Besides, they should also avoid excessive digitization to prevent worsening energy consumption and carbon emissions in the future.

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Conflict of Interest

The authors declare no conflict of interests whatsoever.

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