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Digital development, environmental regulation, and electric power utilization efficiency

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To further promote green and sustainable development, the Chinese government has put forward the carbon peaking and carbon neutrality goals in 2020. As a clean energy, electric power can effectively replace the use of traditional fossil energy and ultimately reduce environmental pollution. Under the relevant background, in order to further explore the impact mechanism of digital development on China's electric power utilization efficiency, a static panel regression model of provincial panel data was established on the basis of measuring the electric power utilization efficiency of 30 provinces in China from 2011 to 2020. The impact of digital development on electric power utilization efficiency of China and the moderating effect of environmental regulation are analyzed. The empirical evidence yields the following conclusions: 1) Digital development has a significant positive impact on the electric power utilization efficiency in China. 2) The results of moderating effect analysis and heterogeneity analysis show that strengthening environmental regulation can promote the improvement of electric power utilization efficiency; Digital development has different impacts on electric power utilization efficiency in the east, central and west of China, especially in the west. 3) In addition, the increase of the Consumer price index of hydropower and fuel and Share of R&D expansion in regional GDP will promote the improvement of electric power utilization efficiency, while the Share of secondary industry in regional GDP will have a negative impact on it.

KEYWORDS

electric power utilization efficiency, digital, intelligence, environmental regulation, cost effect, technology effect

1 Introduction

The excessive use of traditional fossil energy sources, trade openness and urbanization have led to excessive carbon dioxide emissions, and the resulting global climate change problem has become increasingly serious. Therefore, how to scientifically and effectively reduce carbon emission and advocate the use of clean energy has become the focus of attention of all countries [Sun et al. (2020)]. In 2020, China made a commitment to the world to strive to peak carbon dioxide emissions by 2030 and strive to complete the carbon neutral environmental commitment in 2060. This is not only the environmental protection agreement of the Paris Climate Change Agreement, but also China's promises to the world [Huang and Zhai (2021)]. At the same time, driven by Chinese "double carbon" Clean and Green development concept, we need to pay more attention to the effect of emission reduction in key industries such as electricity. In a related research on China, Jiang et al. (2022) studied the structural pollution reduction in Chinese electricity and heating industries using the input-output approach. As an important part of Chinese double carbon target, energy consumption for power supply and Power and Heat industry accounts for 50% of China's total energy consumption, and relevant Chinese companies need to further improve and update their power generation technologies so as to promote carbon emission reduction. In terms of low-carbon development in the construction industry, although the carbon emissions of the construction industry are lower than those of high-energy-consuming industries such as electricity, their carbon emissions should not be neglected in order to achieve the dual-carbon goal. Jiang et al. (2022) conducted a full theoretical analysis and empirical recommendations on carbon emission reduction in China's construction industry, and further improved the existing research on carbon emission reduction of relevant industries from the perspective of input-output analysis. Among the remaining studies on other countries in the world for low carbon, carbon neutral, Yu et al. (2022) evaluated the contribution of several factors such as environmental policies and clean energy to achieve carbon neutral goals in G7 economies, and concluded that countries should abandon the use of fossil fuels to adopt clean energy sources such as electricity, thus making a radical energy change. With China's proposed carbon neutral development goal, carbon reduction actions in developed countries have become a hot issue in climate change. Based on this, Dong et al. (2022) use a research sample of 32 developed countries around the world that proposed carbon neutrality targets and used spatial econometric models to explore the impact of green technology innovation in related industries on carbon emission efficiency in each country.

As a clean energy source, electric power can effectively and steadily replace the use of traditional fossil energy sources, thereby reducing carbon emissions and promoting the country's green and low-carbon energy transition [Kurramovich et al. (2022)]. Therefore, it is imperative to increase the share of electricity in China's energy consumption [Wang and Zhu (2021)]. However, as a major power producing and consuming country, China has experienced local power supply tensions and "power shortages" in recent decades, which have seriously affected the economic development of various regions [Wang and Zhu (2018)], and therefore strong and effective measures must be taken to reduce power losses and improve power utilization efficiency.

On the other hand, the Decision of the Central Committee of the Communist Party of China on Several Major Issues Concerning the Adherence to and Perfection of the Socialist System with Chinese Characteristics and the Modernization of the State's Governance System and Ability to Govern lists "data" as a factor of production for the first time, signifying that data has become the new focus of China's economic development in a period of high quality [Niu (2021)]. As a transformation and reform form of promoting data as a new factor of production, digitalization not only has a positive impact on social and economic development, but also plays a crucial role in environmental and energy consumption. One of the main manifestations of the digital level is the construction of the Internet [Acemoglu and Restrepo (2020)]. Through Internet construction, the gradual replacement of traditional inefficient labor by technologies such as universal artificial intelligence and big data analytics, as well as the technical complementarity of highly skilled personnel, can effectively improve the productivity of various industries, optimize the industrial structure, and promote economic development. At the same time, there is evidence that digital development can improve energy efficiency and reduce energy pollutant emissions, thereby improving the ecological environment [Zhou et al. (2020)]. So, can digital development effectively improve the efficiency of electrical energy use in China? Nowadays, governments around the world increasingly attach importance to environmental protection and green sustainable development strategies. In this context, can the strengthening of environmental regulation by Chinese government play a supporting role in improving the electric power utilization efficiency? Guided by the national policy of vigorously promoting digitalization and green low-carbon behaviors, an in-depth discussion of these questions is of great practical significance to promote the construction of ecological civilization in China and to improve the difficulties of electricity consumption in various regions [Zhang and Xuan (2022); Geng and Cui (2020)].

Based on this, this paper adopts the provincial balanced panel data of China from 2011 to 2020 and measures the level of digital development, environmental regulation intensity and electric power utilization efficiency utilization in each region, analyzes the correlation between the three variables. The regulatory role of environmental regulation is further discussed, and the impact of regional heterogeneity is further investigated.

The main contributions of this paper are as follows. Firstly, in the context of China Green Development, unlike the traditional research on energy efficiency, this paper further refines the research object, calculates the electric energy utilization efficiency index, and conducts an in-depth study on it. Secondly, it innovatively uses a panel data model to systematically explain how digital development affects electric power utilization efficiency, further analyzes the regulatory role of environmental regulation in it, and provides a theoretical reference for improving the inner mechanism of electric power utilization efficiency in the context of Chinese ecological civilization construction. Thirdly, this paper analyzes the difference of electric power utilization efficiency in eastern, western and central China under the regional heterogeneity.

2 Literature review and hypothesis formulation

2.1 Digital development and energy utilization efficiency

With the rapid development of current technology and the comprehensive popularization of the Internet, as well as the wide application of the new generation of artificial intelligence, cloud computing and other new generation of digital technologies, digitalization has greatly enriched social production and life [Pang et al. (2021)]. Ranta and Väisänen (2021) (Ranta et al., 2021) confirm that digitalization can realize circular business models and promote business model innovation. Lukić et al. (2022) argue that digitization can improve the efficiency of urban services and build smart cities. Digital development has greatly improved people's lives, and many researchers have analyzed the relationship between digital development and environmental energy consumption to explore whether digital development can promote the use of environmental energy. Sareen and Haarstad (2021) argue that the development of digitization is the most transformative social drive capable of shaping the next decade, with significant implications for environmental sustainability. The study of Husaini and Lean (2022) focuses on describing digitization can contribute to energy sustainability and achieve increased energy efficiency, although mismanagement of digital development can in turn lead to increased energy consumption. Since the 21st century, with the progress of digital development, energy production efficiency has been improved, reducing industrial energy consumption and improving energy utilization efficiency [Borowski (2021)]. Similarly Pouri (2021) also suggests that digital advancement can improve the efficiency of energy use and consumption from a sustainability perspective.

Most of the current studies focus on energy utilization efficiency. Scholars all over the world have analyzed the impact of energy efficiency from different perspectives. Sun et al. (2021) think that the developing R&D capacity and increasing innovation infrastructure construction can steadily improve the energy efficiency of countries. The progress of environmental technology can help reduce energy consumption in economically developed regions and improve the overall energy efficiency of their respective countries [Paramati et al. (2022)]. Unlike other research ideas, Sun et al. (2022) analyze the impact of government institutions on energy utilization efficiency, and the results show that institutional quality is an important factor to improve energy utilization efficiency.

As China's industrialization continues to accelerate, electric power consumption is also growing, so it is necessary to study digital development and electric power utilization efficiency. Wang and Zhu (2018) use 30 provincial and municipal regions in China from 2002 to 2014 as the research object, based on panel data, to analyze and measure the provincial-level electric energy consumption efficiency and its influencing factors in China, and analyze the heterogeneity of different regions. Wang et al. (2020) assess the inter-provincial electric energy utilization efficiency in China in 2016 based on an output-oriented two-stage DEA approach. Jiang and Cai (2012) analyze 32 industries in Hefei, China, using four different DEA models from multiple perspectives to analyze the industry electric energy input-output efficiency. Qian et al. (2010) measure the Chinese inter-provincial electric energy use efficiency and its change index based on Chinese provincial panel data from 2000 to 2007, and examined the convergence of electric power utilization efficiency in different regions. Therefore, the following hypothesis is proposed in this paper.

Hypothesis 1: Digital development improves the regional electric power utilization efficiency.

2.2 The moderating effect of environmental regulation

Along with the reform and opening, Chinese economy has achieved high growth and the total GDP has jumped to the second in the world. In addition to meeting the emission reduction targets of the Kyoto Protocol, China has also proposed the "30–60″dual carbon target in recent years to strengthen environmental protection and further promote sustainable development. The Chinese government has recognized the importance of environmental protection, and has adopted an environmental policy oriented to industrial waste and carbon dioxide emission reduction. The existing literature shows that the government has recognized that environmental regulation will inhibit economic development, increase government governance costs and enterprise emission reduction costs, and also recognize the difficulties in balancing environmental and economic growth [Wang and Shen (2016)].

In this section, we explain how environmental regulation affect digital development and the electric power utilization efficiency in the following two parts:

2.2.1 Cost effect

The introduction of environmental regulation requires companies to pay additional emission fees for pollution treatment, and for energy-intensive companies such as steel and electricity, government environmental regulation can limit their productivity and profitability. At the same time, companies that do not reduce emissions will be fined by the government, further inhibiting business development. In this paper, we consider the electric power utilization efficiency, which is related to the highly polluting power industry. Although the introduction of environmental regulation will increase the operating costs of enterprises, it will reduce enterprise pollution and promote environmental protection in the long run [Zhao et al. (2015)]. Environmental regulation increase the production cost of enterprises, but digital development can improve the production efficiency of enterprises and reduce the long-term investment of high labor cost, while digitalization-related high technology can improve the enterprises electric power utilization efficiency and optimize their emission reduction strategy, which can offset the additional production cost brought by environmental regulation. Therefore, the higher the level of environmental regulation, the stronger the willingness of enterprises to improve the efficiency of electricity utilization through digital development.

2.2.2 Technology effect

Cheng et al. (2017) suggest that although environmental regulation increase firms' production costs, enterprises also upgrade their production equipment and technology under the influence of environmental regulation, thus improving energy utilization efficiency and labor productivity. At the same time, the emergence of environmental regulation has encouraged enterprises to further optimize resource allocation and improve the efficiency of interdepartmental coordination and management, replacing inefficient behavior. In other words, the emergence of environmental regulation has influenced enterprises' production behavior and increased consumers' environmental awareness [Li et al. (2019)]. Under environmental regulation each enterprise continuously optimizes production management through digital enhancement, develops low-cost and high-efficiency methods to reduce emissions, which in turn counteracts the problem of increased costs brought about by environmental regulation, and ultimately promotes the improvement of electrical energy utilization efficiency. Therefore, the following hypothesis is proposed in this paper.

Hypothesis 2: The higher the level of environmental regulation, the stronger the positive effect of digital development on the electric power utilization efficiency.

3 Research design

3.1 Variables description and data sources

(1) Explained variable. Based on the research of Lin and Dong (2021), Shi and Li (2020), in our paper we use single factor index to

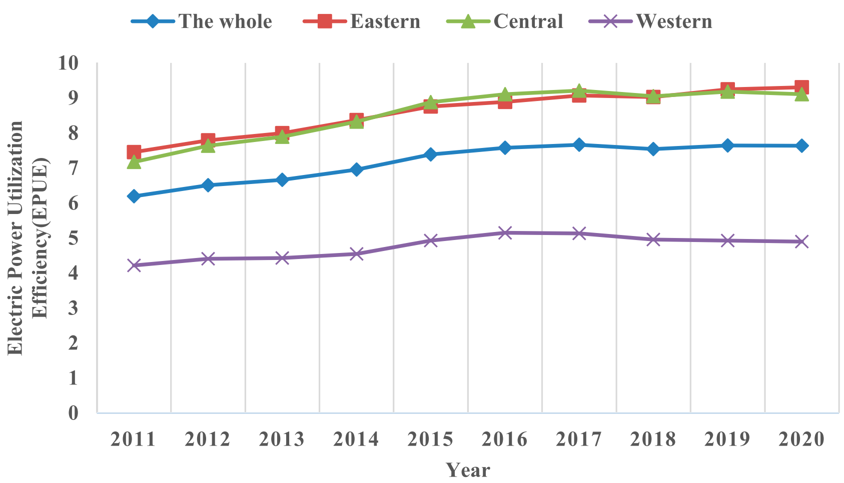

FIGURE 1
The whole of China and regional electric power utilization efficiency from 2011 to 2020 (Ten thousand Yuan/Ton coal equivalent).

measure the important explained variable of electric power utilization efficiency. Compared with the total factor index, the electric power utilization efficiency calculated by the single factor index in this paper ensures the original and accuracy of the data. The specific calculation formula is:

$$\text{Electric Power Utilization Efficiency } (EPUE) = \frac{\text{Regional GDP}}{\text{Electric power consumption}} \tag{1}$$

To make this variable unit more standard, the electric power consumption $(KW \cdot H)$ is converted into tons of standard coal in this paper. $\textbf{Power conversion coefficient} = \mathbf{0.1229}\boldsymbol{kgce/kW \cdot H}$.

The electric power utilization efficiency values of 30 provinces and cities in China from 2011 to 2020 are calculated from Eq. 1, and the average electric power utilization efficiency values of the whole country, the eastern, the central and the western China are calculated, as shown in Figure 1. It can be seen that during this study period, Chinese electric power utilization efficiency is on the rise in general. The average power utilization efficiency in the east and west is higher than the national average, while that in the west is lower than the national average. After 2011, Chinese government departments at all levels gradually began to strengthen environmental protection, and began to use clean energy to replace fossil fuels, which made energy utilization more reasonable. Therefore, after 2011 Chinese overall and regional electric power utilization efficiency gradually improved.

(2) Explanatory variable. Digital development is chosen as the explanatory variable in this paper. Referring to Husaini and Lean (2022), the research concluded that digital development is mainly determined by number of Internet subscribers and number of mobile Internet phone service subscriptions. Therefore, based on the availability of data, the variable: Number of Internet users (*IU*) is chosen as the key explanatory variable to measure the level of digital development in each region of China.

In order to comply with the measurement method of China's relevant statistical yearbook, the specific calculation of this indicator is expressed as: the number of mobile Internet users per 100 people, with reference to the research of Wei et al. (2022), the specific mathematical calculation formula is: cell phone users at the end of the year (10,000)/resident population at the end of the year (10,000) × 100.

In Table 1, this paper shows data tables on the level of digital development in China as a whole and by region from 2011 to 2020. From the table, we can observe that the digital development level in the east is the highest, followed by the west and the center. Under the guidance of relevant policies in China, the western region, which is relatively backward in economic and other development, has made rapid progress in digital development in the last decade.

(3) Moderator variable. Environmental regulation is chosen as the moderator variable in this paper. Environmental regulation refers to the government's policy intervention on polluting enterprises with the fundamental purpose of environmental protection, including direct regulation, economic means and soft means. Considering that the most important source of environmental pollution is industry, and referring to the calculation method of environmental regulation measurement index of Hua and Li (2022), the relative changes of industrial wastewater discharge, industrial soot discharge and industrial sulfur dioxide discharge ("Three Wastes") are calculated as the quantitative expression of environmental regulation intensity (*ERI*) in this paper. The specific calculation of *ERI* is as follows:

Firstly, the data of industrial wastewater discharge, industrial soot discharge and industrial sulfur dioxide discharge of selected cities are standardized, as shown in Eq. 2.

$$EM_{ij}^{s} = \frac{EM_{ij} - \min(EM_j)}{\max(EM_j) - \min(EM_j)} \tag{2}$$

where EM_{ij} represents the emission amount of the j emission pollutant of city i, $\max(EM_j)$ and $\min(EM_j)$ represent the maximum and minimum values of the jth emission pollutant in

TABLE 1 The whole of China and regional the level of digital development from 2011 to 2020 Unit: The number of mobile Internet users per 100 people.

Year	The whole China	Eastern China	Central China	Western China
2011	76.61	94.59	61.26	69.81
2012	86.10	105.82	68.95	78.86
2013	91.99	111.87	74.90	84.54
2014	96.38	116.17	80.20	88.38
2015	94.06	113.12	78.46	86.33
2016	97.39	115.43	81.66	90.79
2017	104.28	119.53	92.17	100.31
2018	114.15	128.86	97.07	111.87
2019	115.62	131.60	99.30	111.52
2020	116.01	127.92	106.07	111.29

TABLE 2 Statistical description of variables.

Variable	Definition	Mean	Max	Min	Std. dev	Unit
EPUE	Electric power utilization efficiency	7.1733	14.2839	1.1348	3.1616	Ten thousand Yuan/Ton coal equivalent
IU	Number of Internet users	84.3381	249.9210	0.6110	49.2610	Ten thousand people
ERI	Environmental regulation intensity	0.5251	2.5853	0.0001	0.5328	–
P	Consumer price index of hydropower and fuel	1.7809	2.4201	1.2431	0.2558	–
RD	Share of R&D expenditure in regional GDP	0.0167	0.0644	0.0041	0.0114	%
SS	Share of secondary industry in regional GDP	0.4313	0.5900	0.1580	0.0877	%

the city, and s represents the standardized value of the j emission pollutant of city i. Next, calculate the proportion of each emission pollutant in the comprehensive index:

$$W_j = \frac{EM}{\overline{EM_{ij}}} \quad (3)$$

$\overline{EM_{ij}}$ represents the average emission level of j pollutant in 30 cities in each year. Finally, the comprehensive environmental regulation index of city i is obtained.

$$ERI_i = \frac{\sum_{j=1}^{3} W_j EM_{ij}^s}{3} \quad (4)$$

The environmental regulation intensity in each city and province is calculated by the above method, so when the emission of "Three Wastes" is lower, it means that the environmental regulation intensity (*ERI*) of the city and region is stronger.

In addition, the model may also be affected by the absence of variables, so this paper considers the following control variables in the model.

(4) Control variables. Three control variables are chosen in this paper, the details are as follows:
   (1) Consumer price index of hydropower and fuel (*P*)
   (2) Proportion of R & D expenditure in GDP (*RD*)
   (3) Proportion of GDP of secondary industry (*SS*)

Table 2 shows the statistical description of the variables. The above indicators are obtained through 2011–2020 China Statistical Yearbook, China Power Yearbook, China Urban Statistical Yearbook, China Science and technology statistical yearbook and China Environmental Statistical Yearbook. At the same time, relevant variables are expressed in 2000 prices.

3.2 Model building

Referring to Zhang and Xuan (2022), this paper first analyzes the impact of digital development level and environmental regulation on regional electric power utilization efficiency using a static panel model:

$$EPUE_{it} = \alpha_0 + \alpha_1 IU_{i,t} + \alpha_2 ERI_{i,t} + \sum_\beta \theta_\beta Con_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (5)$$

Where, $EPUE_{i,t}$ is the explained variable, representing the electric power utilization efficiency of province i in year t. $IU_{i,t}$ is the core explanatory variable, which is used to measure the digital development level. $ERI_{i,t}$ is the variable of environmental regulation. $Con_{i,t}$ is the control variable added to the model, the rest μ_i is the individual fixed effect, γ_t is the time fixed effect, $\varepsilon_{i,t}$ is the random disturbance term and obeys the normal distribution.

Then this paper continues to add the interaction term between environmental regulation and digitalization based on the above basic model to analyze the regulatory role of environmental regulation. The specific model is as follows.

TABLE 3 Benchmark regression results.

Variable	(1) OLS	(2) FE	(3) RE
ln*IU*	0.369*** (2.800)	0.141** (2.570)	0.142** (2.540)
ln*ERI*		−0.073** (−2.580)	−0.079*** (−2.790)
ln*P*		0.524** (2.520)	0.259 (1.330)
RD		8.012*** (2.620)	11.008*** (3.820)
SS		−0.452*** (−2.990)	−0.458*** (−2.980)
Constant	0.156 (0.260)	1.001*** (3.530)	1.102*** (3.680)
Observations	300	300	300
Adj.R^2	0.022	0.436	0.431

$$EPUE_{i,t} = \alpha_0 + \alpha_1 IU_{i,t} + \alpha_2 ERI_{i,t} + \alpha_3 IU_{i,t} \times ERI_{i,t} + \sum_\beta \theta_\beta Con_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \tag{6}$$

Now $ERI_{i,t}$ is the moderator variable, mainly referring to the environmental regulation intensity calculated from the regional "Three Wastes" emission.

4 Empirical results

4.1 Benchmark regression results

Table 3 reports the linear estimation results of the impact of digital development level and environmental regulation intensity on electric power utilization efficiency.

Table 3 is the basic regression results of the empirical part of this paper. Where column (1) is the basic results of OLS regression between the explanatory variable and the explained variable. With a coefficient of 0.369, indicating that for every 1% increase in digital development level, the electric power utilization efficiency will increase by 0.369%. To make the regression empirical results more convincing, this paper carries out panel fixed effect and random effect regression, and to test the endogenous problem of the model, Hausman test is carried out. The p-value of the result is $0.0277 < 0.05$, which indicates that the fixed effect model column (2) is more effective. Therefore, the following studies are all based on the results of the fixed effect model. On the basis that both the fixed effect regression model and parameter estimation are valid, we will further check the regression results of each parameter and explain its meaning.

(1) Digital development level. The number of Internet users (*IU*), although its coefficient is small (0.141), has a positive impact on the power utilization efficiency of various regions, which is the same as the research conclusion of most scholars, so it is in line with the economic significance.
(2) Environmental regulation intensity (ERI). The symbol of the environmental regulation intensity coefficient calculated based on the "Three Wastes" emissions of each city is negative, indicating that less pollutant emissions will improve the power utilization efficiency. When the emission of "Three Wastes" is reduced, indicating that for every 1% increase in environmental regulation intensity, the electric power utilization efficiency will decrease by 0.073%.
(3) Other control variables. The regression coefficient of the consumer price index of hydropower and fuel *P*) is 0.524, which indicates that the power price index variable is positively related to the electric power utilization efficiency, and the improvement of the power price index is conducive to the improvement of the electric power utilization efficiency. The regression coefficient of the proportion of GDP of the secondary industry (*SS*) is −0.452, indicating that the proportion of industrial output value is negatively related to the electric power utilization efficiency. For every 1% decrease in GDP of the secondary industry, the efficiency of power utilization will increase by 0.452%. Share of R&D expenditure in regional GDP (*RD*) is positively correlated with electric power utilization efficiency, and the degree of influence is the largest, with a coefficient of 8.012.

In the analysis of the above basic regression results, this paper has added the variable factors that mainly affect the electric power utilization efficiency, but the potential endogenous problems may still lead to the deviation of the panel regression model results.

TABLE 4 The moderation effect of environmental regulation intensity.

Variable	(1)FE	(2)FE	(3)RE
ln*IU*	0.141** (2.570)	0.164*** (2.970)	0.163*** (2.920)
ln*ERI*	−0.073** (−2.580)	−0.029 (−0.880)	−0.037 (−1.100)
ln*IU* × ln*ERI*		−0.032** (−2.540)	−0.029** (−2.380)
ln*P*	0.524** (2.520)	0.482** (2.340)	0.252 (1.300)
RD	8.012*** (2.620)	7.289** (2.400)	10.070*** (3.490)
SS	−0.452*** (−2.990)	−0.443*** (−2.960)	−0.443*** (−2.920)
Constant	1.001*** (3.530)	0.902*** (3.190)	0.994*** (3.320)
Observations	300	300	300
Adj.R^2	0.436	0.449	0.445

4.2 Moderating effect

Next this paper adds adjustment variables, that is, the regression of interaction terms, based on the fixed effect model. See Table 4 below for details.

In Table 4, where column (1) is the basic regression result of the fixed effect model. At the same time, environmental regulation intensity is the key driving factor of national and regional economic and energy environment development. Appropriate environmental regulation can promote the digital process and promote the improvement of electric power utilization efficiency. Therefore, the interaction term between environmental regulation intensity and digital development level is added to the basic regression model. See column (2) for the specific regression results. At the same time, the coefficient of the interaction term is significantly negative,

TABLE 5 Regional heterogeneity.

Variable	Full sample		Eastern		Central		Western	
	FE	FE	FE	FE	FE	FE	FE	FE
ln*IU*	0.141** (2.570)	0.164*** (2.970)	−0.026 (−0.300)	0.006 (2.070)	0.131 (1.200)	0.175* (1.680)	0.262** (2.520)	0.250** (2.380)
ln*ERI*	−0.073** (−2.580)	−0.029 (−0.880)	−0.005 (−0.160)	0.019 (0.620)	−0.142*** (−3.530)	0.069 (0.870)	−0.127* (−1.700)	−0.229 (−1.560)
ln*IU* × ln*ERI*		−0.032** (−2.540)		−0.026*** (−2.740)		−0.132*** (−3.030)		0.051 (0.810)
ln*P*	0.524** (2.520)	0.482** (2.340)	0.850*** (3.180)	0.738*** (2.820)	−0.119 (−0.350)	−0.104 (−0.320)	0.432 (1.010)	0.387 (0.900)
RD	8.012*** (2.620)	7.289** (2.400)	5.156 (1.550)	4.353 (1.350)	2.081 (0.410)	2.544 (0.530)	14.107 (1.510)	13.692 (1.460)
SS	−0.452*** (−2.990)	−0.443*** (−2.960)	−0.954*** (−4.490)	−0.940*** (−4.57)	−0.854*** (−3.790)	−0.859*** (−4.040)	0.207 (0.680)	0.215 (0.700)
Constant	1.001*** (3.530)	0.902*** (3.190)	2.102*** (5.070)	1.986*** (4.920)	2.008*** (4.040)	1.767*** (3.720)	−0.268 (−0.490)	−0.153 (−0.270)
Observations	300	300	110	110	80	80	110	110
Adj.R^2	0.436	0.449	0.631	0.659	0.689	0.727	0.300	0.305

indicating that the regulatory effect of environmental regulation intensity is significant and effective.

In the previous benchmark fixed effect regression results, it is shown that the environmental regulation intensity (*ERI*) has a negative impact on electric energy utilization efficiency, and the digital development level has a positive impact on electric power utilization efficiency. Therefore, the coefficient of the interaction term between the two variables is negative, and the theoretical and practical significance are in line with the reality. The reduction of "Three Wastes" emissions and the improvement of environmental regulation intensity are negatively correlated with the impact of digital development on the electric power utilization efficiency, which can improve the electric power utilization efficiency.

4.3 Heterogeneity analysis

Considering the analysis of the full sample data, the impact of heterogeneity of different policies or regional development on electric power utilization efficiency may be ignored. However, the process of digital development level may depend on the regional development process. Especially for the fast-growing western region since the 21st century under the national policy of western development, the implementation efficiency of digital development level will promote the faster improvement of electric power utilization efficiency in the western region.

Therefore, this paper divides the 30 provinces and cities studied in this paper into three regions: the eastern, central, and western China. As shown in Table 5, the digital development level in the western China has a stronger promoting effect on the electric power utilization efficiency than in the case of the full sample. At the same time, environmental regulation intensity has a stronger promoting effect on the electric power utilization efficiency.

At the same time, under the policy background of the West to East Power Transmission Project proposed by China since the 21st century, the improvement of electric power utilization efficiency by digital development is more obvious, which also fully shows that the impact effect of digital development level and environmental regulation intensity in the western region on power utilization efficiency is better than that in the eastern and central regions.

TABLE 6 Robustness test 1: Replace core independent variable.

Variable	(1)FE	(2)FE	(3)FE
ln*IU*	0.141** (2.570)		
ln*RID*		0.048*** (3.760)	
ln*DIG*			0.076*** (3.590)
ln*ERI*	−0.073** (−2.580)	−0.075*** (−2.720)	−0.081*** (−2.880)
ln*P*	Yes	Yes	Yes
RD	Yes	Yes	Yes
SS	Yes	Yes	Yes
Constant	Yes	Yes	Yes
Observations	300	300	300
Adj.R^2	0.436	0.449	0.445

4.4 Robustness analysis

The robustness test in this paper mainly involves changing the core explanatory variable, removing the control variables and changing the sample interval. The robustness results show that the sign and significance of the regression coefficients of the two such variables have not changed significantly, and the degree of influence on the electric power utilization efficiency variable is relatively stable, which ensures the robustness of the regression results.

4.4.1 Replace core explanatory variable

Since different digital development level balance indicators will have different effects on power utilization efficiency, the impact on the core explained variables can be observed by changing different measurement indicators, and the differences

TABLE 7 Robustness test 2: Excluded variables.

	Excluded variables						
	P	*RD*	*SS*	*P, RD*	*P, SS*	*RD, SS*	*P, RD, SS*
ln*IU*	0.179*** (3.360)	0.179*** (3.340)	0.240*** (5.390)	0.240*** (4.730)	0.287*** (6.930)	0.308*** (7.780)	0.394*** (12.240)
ln*ERI*	−0.086*** (−3.050)	−0.600** (−2.140)	−0.073** (−2.540)	−0.073*** (−2.600)	−0.087*** (−3.040)	−0.057** (−1.990)	−0.072** (−2.470)
ln*P*	No	Yes	Yes	No	No	Yes	No
RD	Yes	No	Yes	No	Yes	No	No
SS	Yes	Yes	No	Yes	No	No	No
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	300	300	300	300	300	300	300
Adj.R^2	0.422	0.421	0.417	0.399	0.401	0.394	0.366

TABLE 8 Robustness test 3: Change the sample interval.

	Excluded the 2020 and 2019	Excluded the 2020
ln*IU*	0.184*** (2.920)	0.172*** (2.910)
ln*ERI*	−0.062* (−1.670)	−0.068** (−2.390)
ln*P*	Yes	Yes
RD	Yes	Yes
SS	Yes	Yes
Constant	Yes	Yes
Observations	240	270
Adj.R^2	0.473	0.455

can be distinguished. In this paper, two different digital development level balance indicators are proposed: 1) Robot installation density (single factor); 2) Digital comprehensive index (all factors). Specifically, it is measured by the Internet penetration rate, the number of employees in Internet related industries, the Internet related output, the number of Internet users, and the digital inclusive finance index. On this basis, the entropy method is used to calculate the comprehensive digital development level of each region. The final examine results are shown in Table 6.

The robot installation density and digital comprehensive index are successively substituted into the basic fixed effect regression model, and the results are shown in column (2) and column (3) of Table 6. The replaced core explanatory variable also has a significant positive correlation effect on electric power utilization efficiency, further proving that digital development will improve power utilization efficiency. The empirical results of this test method fully illustrate that the research conclusions of this paper are robust.

4.4.2 Remove the control variables

By removing the control variables, we will focus on testing whether the estimation coefficient results of IU and ERI are robust. The results in Table 7 show that after removing the control variables one by one, the symbols of the key variable coefficients do not change, and the degree of influence on electric power utilization efficiency does not change much, which proves that the research conclusion of this paper is robust.

4.4.3 Change the sample interval

Since 2019, the COVID-19 epidemic has broken out in China and other countries in the world, and the trade blockade of various countries in the world has also had a great impact on the energy market. To ensure the reliability of the empirical results and prevent the emergence of outliers, we delete the 2020 data or the 2019 and 2020 data. In this paper, the model is re-estimated, and Table 8 shows that there is no significant difference between the two key research variables and the estimated parameters of the original regression model in terms of sign and coefficient size, so it can be considered that the conclusion has passed the robustness test.

5 Conclusion, recommendations, and limitations

This paper measures the electric power utilization efficiency of 30 Chinese provinces from 2011 to 2020, and empirically analyzes the impact of digitalization on it using provincial equilibrium panel data over a 10-year period, and further discusses the moderating role of environmental regulation intensity, and analyzes the impact of regional heterogeneity with respect to the regional distribution characteristics of China, and finally conducts robustness tests to prove the reliability of the theoretical model. Based on this study, the following conclusions are obtained:

(1) The level of digitalization will improve the electric power utilization efficiency use in each region of China.
(2) Greater intensity of environmental regulation will promote more efficient use of electricity and energy.
(3) The power price related index and the share of R&D funding will have a positive effect on the efficiency of electric power use, but the increase of the share of secondary industry will have a negative effect on the efficiency of electric energy use.
(4) The influence of digital development level on electric power utilization efficiency varies in different regions of China. Influenced by relevant development policies, the level of digital development has a significant positive impact on the electric power utilization efficiency in the western region, while it has no significant impact on it in the central and eastern regions.

The research in this paper shows that digital development can improve the electric power utilization efficiency, and environmental regulation intensity can also regulate the relationship between digitalization and electric power utilization efficiency, and the strength of the role of digitalization varies from region to region. Therefore, this paper proposes the following suggestions to promote the efficiency of electric energy utilization by improving the digital development level, improving, and strengthening the environmental regulation intensity, increasing the investment of R&D funds, and optimizing the industrial structure: First, the level of digital development in various regions needs to be further improved to give full play to the role of digitalization in promoting electric power utilization efficiency. It is necessary to further improve the network infrastructure construction as well as enhance the network infrastructure service capacity and increase the investment in digital innovation. Internet is an important development carrier of new generation science and technology. It is important for Internet enterprises to expand Internet users and improve the public's awareness of Internet related technologies. At the same time, governments at all levels should make full use of industrial subsidies, tax relief and other policies to increase 5G investment and construction, increase investment in robot industry, and further popularize advanced digital technology. Second, in combination with the current development status of electric power enterprises in various regions, interregional technology exchange and cooperation should be strengthened, and the advanced electric power development experience in the western region should be extended to the central and eastern regions. Third, the government should increase investment in environmental protection, strengthen environmental regulation intensity, and improve the efficiency of energy use in all regions. The government should give certain environmental incentive policy to clean production enterprises, increase the penalties for illegal and unlawful emissions enterprises, and the state should advocate the introduction of advanced environmental protection and emission reduction technologies from the east to the western region, where pollution is a serious problem.

However, based on this study, there are some limitations in this paper. First, limited by the collection of energy consumption and electricity-related data, the data sample in this paper is small, and its panel regression results only reflect the situation from 2011 to 2020. When data can be collected completely, the sample size should be increased, and comparative analysis and research should be conducted on other countries similar to China. In addition, the control variables considered in this paper may not be comprehensive enough, and the influence variables will be added in the subsequent study in conjunction with other researchers' studies. Finally, the heterogeneity analysis in this paper only classifies China into three situations: East, West, and West, which may not be able to analyse the development of different provinces and regions in a more specific way.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

HZ writed and desiged for the research. QO, XY, and JH analysed the model and drafted the paper. WT issued the idea and drafted the paper. All authors contributed to revise the paper critically.

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Conflict of interest

HZ, QO, and XY were employed by Beijing FibrLink Communications Co., Ltd., State Grid Information & Telecommunication Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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