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The impact of climate change and environmental regulation on energy poverty: evidence from China

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Abstract

Background Environmental pollution and energy poverty have always been serious challenges for the global energy system.

Results Based on the panel data of 30 provinces in China from 2005 to 2020, this paper uses FE and sys-GMM models to explore the impact of environmental regulations and climate change on energy poverty. The results show that climate change increases energy poverty, with rising energy for cooling in hot summers, and unchanged income in the short term. Moreover, environmental regulation plays a moderating role between climate change and energy poverty. Specifically, economical environmental regulation has a negative moderating effect, while legal and supervised environmental regulations have positive moderating effects. Finally, the national basic energy poverty line used is lower than that in the eastern region, higher than that in the western region, and close to that in the central region, which reflects the heterogeneity of energy poverty in different regions of China.

Conclusions The findings in this paper clarify the nexus between climate change, environmental regulation, and energy poverty, addressing in this way a gap in existing research, which has great significance for environmental and energy policy makers.

Keywords Energy poverty, Environmental regulation, Climate change, Geographical location, Extended linear expenditure system

Background

Poverty is a worldwide problem that needs to be solved urgently [1]. Energy poverty, as a form of poverty, is recognized by the United Nations and other international organizations. This requires the government to pay more attention to energy poverty on the basis of eliminating income poverty [2]. As the largest developing country and energy consumer in the world, China's economic growth has long relied on the consumption of traditional energy, which has brought about a series of energy, climate and environmental problems, such as energy shortage, frequent extreme weather, and continuous environmental degradation [3]. Therefore, it is urgent to establish a long-term mechanism to solve environmental problems and energy poverty. As an effective policy tool

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to solve energy, climate, and environmental problems, environmental regulation could significantly improve energy efficiency, reduce carbon emissions and improve the ecological environment [4, 5]. In this context, this paper examines the linkage between climate change, environmental regulation and energy poverty.

To some extent, eliminating energy poverty is a political process [6]. To cope with energy poverty, the Chinese government has implemented environmental regulation and poverty alleviation policies, providing more policy support to green environmental protection enterprises. Specifically, for the purpose of environmental protection and resource allocation, the government directly or indirectly intervenes in the production and operation activities of enterprises by using formal environmental regulations, such as administrative systems and economic means, to promote enterprises, enhance the technological innovation capabilities, optimize industrial structure, and achieve green transformation [7, 8]. Furthermore, the government has also established informal environmental regulations, such as peer supervision and public supervision, to assist in the effective implementation of formal environmental regulations by promoting the concept of green environmental protection, which is also an effective way to mitigate climate change and reduce energy poverty [9].

Moreover, the effect of temperature increases, due to climate change, are expected to aggravate the demand for energy [10]. Some scholars decompose the energy poverty impact into the effect of temperature on energy expenditure and income, who find that both channels operate via heat stress, but not cold stress [11]. To summarize, there are at least two ways how higher temperatures could theoretically increase the incidence of energy poverty. Firstly, higher temperatures will augment energy consumption for cooling needs [12, 13]. Secondly, in order to avoid the discomfort caused by high temperature, people will increase the time of indoor activities, thus raising the energy consumption of entertainment projects [14]. However, the impact of climate change on energy poverty has two facets. With the increase of temperature, the incidence of energy poverty in extremely cold weather can be reduced, but it is not conducive to alleviating energy poverty under normal temperature [15, 16].

The existing research on energy poverty mainly focuses on the causes, adverse effects, and measurement methods of energy poverty [17, 18], as well as the impact of energy poverty on household life and energy policy [19, 20]. In addition, some studies have explored the influence of energy poverty on climate change, believing that effective policy design can achieve a win–win situation between reducing energy poverty and mitigating climate change [16, 21]. Nevertheless, few studies have investigated the impact of climate change on energy poverty, especially the specific role of environmental regulation. Therefore, based on China's provincial panel data, this paper uses FE and sys-GMM models to examine the impact of climate change, environmental regulation on energy poverty, which would help improve the usage of traditional energy, alleviate extreme weather changes, and reduce the incidence of energy poverty.

The rest of this article is organized as follows. Literature review summaries mainstream research perspectives. Methods discloses the mechanism between climate change and environmental regulation on energy poverty and introduces the models and measurements. Results examines the impact of climate change and environmental regulation on energy poverty and the moderating effect of the different types of environmental regulation. Conclusions and policy implications concludes the main viewpoints of this article. The main contributions of this paper are as follows: First, the existing research lacks a discussion on the relationship between climate change and energy poverty, as well as the environmental regulation and energy poverty, especially on the moderating effect of environmental regulation. Based on the China's provincial panel data, this paper uses FE and sys-GMM models to examine the impact of climate change on energy poverty, and the moderating effect of environmental regulation in the relationship between climate change and energy poverty, which enriches the existing literature on energy poverty. Second, considering the significant differences of various types of environmental regulations, this paper further investigates the heterogeneity of the moderating effect of economical, legal, and supervised environmental regulations in the relationship between climate change and energy poverty, which helps the government adopt differentiated environmental regulation policies to coordinate the relationship between climate change and energy poverty. Third, since there are significant differences in household energy consumption expenditure in different regions of China, this paper uses the extend linear expenditure system (ELES) model to calculate the poverty line of energy consumption expenditure in eastern, central, and western China, respectively, to reflect the energy poverty situation of each province, which considers not only the impact of expenditure on energy demand but also the impact of other exogenous factors. In addition, owing to the large span of China's north–south dimension, this paper introduces geographical location (measured by the geographical latitude north and south) as a control variable to comprehensively and accurately explore the impact of climate change and environmental regulation on energy poverty.

Literature review

Energy poverty and climate change

Energy poverty and climate change are two major problems affecting human sustainable development [2]. Initially, energy poverty meant that people's economic conditions cannot afford the necessary living energy needs [23]. With the deepening of the exploration of energy poverty, the research object has gradually developed from the energy demand to ensure basic survival to facilitating high-quality life, safety, and environmental protection. The research dimension has also expanded from the energy expenditure burden to the lack of access to energy services and energy management capabilities [24].

Energy poverty is closely related to climate change, but different scholars have various views. Bouzarovski et al. [25] believes that the mitigation of climate change and the policies adopted to promote the development of renewable energy and energy transformation will aggravate the degree of energy poverty. Meanwhile, temperature shocks could also lead to an increase in energy poverty [10]. However, some scholars have put forward the opposite view. Churchill et al. [16] found that although the energy poverty rate will increase slightly within a certain temperature range, medium and long-term global warming is conducive to alleviating energy poverty in cold regions. Others hold a neutral view that a synergistic mechanism should be established to mitigate climate change and eliminate energy poverty [21].

Furthermore, from the perspective of the impact mechanism of climate change on energy poverty, many scholars also put forward different views. Li et al. [22] argues that as the use of solid fuels leads to the deterioration of the external climate environment, the government has introduced a series of environmental measures to adjust the energy structure, resulting in energy poverty. Feeny et al. [10] also observed that climate change hindered crop production, reduced household income, increased the burden of energy consumption, and exacerbated energy poverty. Besides, Campagnolo and Ca (2022) [26] assessed that the impact of climate change on household energy demand is regressive, adding to the already regressive effects of a carbon tax, and affecting the income level of residents. In general, most studies have discussed the mechanism of climate change on energy poverty based on the policies and income perspectives.

Environmental regulation and energy poverty

The impact mechanism of environmental regulation on energy poverty is complex. Some scholars believe that environmental regulation will aggravate the occurrence of energy poverty to a certain extent. There are two main transmission mechanisms. On one hand, environmental regulation will exacerbate energy poverty by affecting energy prices. Environmental pollution and excessive greenhouse gas emissions caused by energy production and consumption have a serious negative impact on human production and quality of life [27]. A series of environmental regulations implemented in response to these negative effects have caused fluctuations in energy prices. From the perspective of residents, the burden of household energy consumption has increased, exacerbating the problem of energy poverty [6]. From a corporate perspective, many industrial enterprises have had to cut production or even temporarily close factories due to rising energy prices and soaring cost, and residents' energy consumption expenditures have increased significantly, pushing many households into "energy poverty" [28]. On the other hand, the environmental regulation will aggravate energy poverty through energy structure optimization policies. For example, in China, farmers have been prohibited from using conventional fuels (mainly coal) for cooking or heating, but these farmer households often cannot afford the cost of gas and gas pipelines [29].

However, other scholars have proposed the opposite point of view that appropriate environmental regulation can reduce energy poverty. Households can reduce energy poverty by gradually shifting to a carbon-free environment through policies that directly reduce the carbon emissions [30]. Indirect carbon reduction policies, such as an oil tax and the creation of "pro-poor energy" funds, can reduce carbon emission and alleviate energy poverty [31]. Similarly, Hyder [32] and Winkler [33] argued that a carbon tax would reduce not only CO_2 emissions but also energy poverty. At the same time, from the perspective of carbon trading, the implementation of individual carbon trading systems can indeed effectively improve energy poverty [2]. In short, most of the existing studies discuss the relationship between environmental regulation and energy poverty from the perspective of carbon emissions.

Climate change and environmental regulation

There is a two-way transmission between climate change and environmental regulation. First, environmental regulation is the key measure for China to achieve the "dual carbon" goal, namely, carbon peak and carbon neutralization [34], which can mitigate climate change by reducing carbon emissions. There are not only an inverted “U”relationship between environmental regulation and carbon emissions [35], but also regional differences and threshold effects However, it should be noted that the strictness of public governance will affect the effect of environmental regulation on climate change [36, 37]. Woon et al. [38] also pointed out that the environmental damage caused by carbon emissions should be the responsibility of the relevant institutions. At the same time, Danish et al. [39] show that environmental regulation has a significant negative impact on carbon dioxide emissions in BRICS countries. The promulgation of strong new climate change regulations (i.e., amendments, decrees, and orders) at the rule of law has greatly reduced carbon dioxide emissions, but the efficiency of environmental legislation must be supported by regulatory agencies that effectively enforce the law [40].

In addition, as global climate and environmental issues have become increasingly prominent, the task of energy conservation is imminent. Governments are committed to exploring feasible ways to reduce carbon emissions while increase social welfare, and moderate environmental regulation has achieved remarkable results. In China, especially after the establishment of a unified carbon market, the carbon market policies have had a sustained positive impact on energy conservation and emission reduction [41], but the synergistic effect of environmental regulation policies has a significant heterogeneous impact on different levels of carbon emissions [42]. And according to the principle of Pigou tax, environmental regulation can improve the impact of climate change by reducing the carbon emissions of enterprises through measures such as environmental taxes. Therefore, some scholars believe that environmental taxes play an important role in enhancing the synergy between pollution reduction and carbon emission reduction [43].

Climate change, environmental regulation, and energy poverty There is no unified view on the relationship between climate change, energy poverty, and environmental regulation. On one hand, a series of environmental policies to address climate change will have an impact on energy. For example, in recent years, China has formulated very strict environmental regulations to cope with climate change, but stricter environmental regulations have led to greater economic burdens for households using non-clean energy and exacerbated their energy poverty [44]. On the other hand, more strict environmental regulation will also cause climate problems. According to the "green paradox," producers expect that environmental regulation will reduce their revenues, thus accelerating extraction and reducing energy prices, which in turn leads to more carbon dioxide emissions and further climate deterioration [45, 46]. At the same time, under different energy consumption structures, the impact of environmental regulation on TFP is uncertain. When there is substantial consumption of fossil fuels, it exerts a negative impact on TFP, thereby hindering the improvement of social welfare [47].

In response to the problem of energy poverty, countries are committed to introducing various policies aimed at its alleviation. The “Energy Efficiency Obligation” initiative implemented by the United Kingdom has greatly alleviated the country’s energy poverty problem, but inappropriate climate policies are likely to lead to new forms of inequality. Therefore, countries should pay attention to achieve a fair change when dealing with energy poverty and climate change in the future [48, 49]. Additionally, some developing countries have suffered varying degrees of health damage due to insufficient energy infrastructure [50]. However, energy poverty will also aggravate environmental pressure. Hassan et al. [51] found that economic growth, income inequality, and energy poverty have aggravated the environmental pressure of the BRICS countries. At the same time, the United Kingdom and France, as representatives of developed countries, also incorporate energy poverty into relevant policies [52]. There is a close relationship between climate change, environmental regulation, and energy poverty, but the existing research lacks the discussion of their interaction mechanism.

Comprehensive review

As in the research between climate change, environmental regulation, and energy poverty, most studies only discuss the relationship between two of them, few scholars have taken the interaction mechanism among climate change, environmental regulation, and energy poverty as the research object from the macro perspective. At the same time, few studies pay attention to the moderating effect of environmental regulation in the relationship between climate change and energy poverty. Based on this, the FE and sys-GMM model are used in this paper to clarify the nexus between three variables, which helps government and companies increasingly improve the energy situation.

Methods

Theoretical model

The internal mechanism of the impact of climate change and environmental regulation on energy poverty from the theoretical level is analyzed in this paper. As shown in Fig. 1, firstly, the climate change has direct effect on energy poverty. Climate change has led to more extreme precipitation patterns in different spaces. Areas with abundant precipitation experience increased humidity, and arid places become more arid, thereby accentuating the scarcity of water resources in some areas. Likewise, elevated temperature caused by climate change will increase the energy cost for individuals, driven by the increased cooling demand. Especially in a hot summer, the irregular precipitation makes hydropower unable to

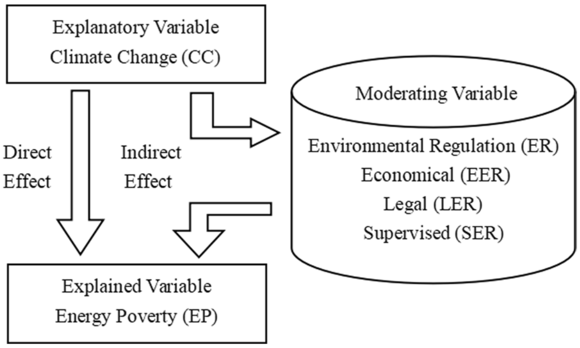

Fig. 1 The impact mechanism of CC and ER on EP

meet the normal needs and affects the operation of the economy and society. In addition, extreme higher or lower temperatures will weaken the working efficiency of various energy facilities, increase the probability of failure and the difficulty of operation and maintenance, which may reduce the scale of energy production. At the same time, extreme weather such as heavy rains, tropical cyclones, and freezing disasters often cause direct damage to various energy infrastructures, greatly reducing energy supply efficiency, which is not conducive to alleviating energy poverty.

Secondly, the climate change has indirect effect on energy poverty through environmental regulation. With continuous use of fossil energy, the concentration of greenhouse gases has increased significantly, leading to global warming and a series of environmental problems. In order to mitigate climate change, improve environmental problems, and promote energy transformation, many countries have implemented different environmental protection policies, such as environmental regulation. On one hand, the energy transformation represented by clean energy may aggravate the energy use cost of energy poor groups, which is not conducive to energy poverty reduction. On the other hand, under the pressure of environmental regulation, energy enterprises might optimize the production structure through technological innovation to enhance market competitiveness, which is conducive to reducing pollution emissions, improving the ecological environment and enhancing the energy supply capacity. Therefore, the role of environmental regulation with regard to the impact of climate change on energy poverty is double sided.

Models and measurements

Models

In this paper, the system generalized method of moments (sys-GMM) is used to estimate the impact of climate change on energy poverty [53]. This method can better deal with the autocorrelation and endogenous problems of energy poverty. Panel regression models are established, such as model (1):

$$\mathrm{EP_{it}} = \alpha_0 + \alpha_1 \mathrm{CC_{it}} + \alpha_2 \mathrm{CONTROL_{it}} + \theta_{\mathrm{it}} \,. \tag{1}$$

EP is the explained variable indicating energy poverty. CC is the explanatory variable representing climate change. i and t represent the province and the year, respectively. In order to control the impact of other variables on energy poverty, $\mathrm{CONTROL_{it}}$ represents control variable in this paper. α_0 denotes the constant term, α_1 and α_2 denote the coefficients of the explanatory variables and control variables, respectively. θ_{it} represents the random disturbance term.

In addition, in order to study the regulatory role of environmental regulations (ER) in the impact of climate change on energy poverty, this paper also adds the variable of environmental regulations (ER). Equation (2) illustrates the relationship between ER and EP. In Eq. (3), $CC_{it} \times ER_{it}$ represents the regulatory effect of ER on the impact of CC on EP. β_0 and γ_0 represent constant terms. β_1 and γ_1 are the coefficients of the independent variables. γ_2 is the coefficient of the cross term of CC and ER. β_2 and γ_3 are the coefficients of the control variables. μ_{it} and φ_{it} represent the random disturbance term.

$$\mathrm{EP_{it}} = \beta_0 + \beta_1 \mathrm{ER_{it}} + \beta_2 \mathrm{CONTROL}_{\mathrm{it}} + \mu_{\mathrm{it}} \,, \tag{2}$$

$$\begin{aligned} \mathrm{EP_{it}} = \gamma_0 + \gamma_1 \mathrm{CC_{it}} + \gamma_2 \mathrm{CC_{it}} \times \mathrm{ER_{it}} \\ + \gamma_3 \mathrm{CONTROL}_{\mathrm{it}} + \varphi_{\mathrm{it}}. \end{aligned} \tag{3}$$

Definition of variables

Energy poverty Okushima assesses energy poverty through a direct measure of energy service use, exploring the regional characteristics of energy or fuel poverty in Japan through a new methodology. The measure is a calorific relative poverty measure with multiple thresholds reflecting the diverse energy needs of households. Heindl [54] thinks that fuel-poverty measurement consists of two independent parts including the definition of an appropriate fuel-poverty line and techniques to measure fuel poverty. Wang et al. [55] categorized energy poverty indicators into three categories, availability of energy services, quality of energy services and human survival and development energy demand satisfaction, and constructed a comprehensive energy poverty evaluation index to evaluate regional energy poverty in China. Qurat-ul-Ann and Mirza [56] used a multidimensional energy poverty index to estimate the prevalence and intensity of multidimensional energy poverty at the household level in Pakistan with seven dimensions of weighting. Ssennono et al. [57] adopted a multidimensional nature of measuring energy poverty and enhanced multidimensional energy poverty measurement. Qeqe et al. [58] examined the relationship between electricity prices and household welfare in South Africa based on a linear expenditure system model (LES). The study applied a demand system framework to time series data from 2000 to 2018, and the analysis involved the calculation of price elasticities and the measurement of welfare changes. The impact of electricity pricing policies on the cost of living (represented by the consumer price index and household expenditure patterns) is also considered. In this paper, the extended linear expenditure system model (ELES) is used to measure the poverty line of energy consumption expenditure to reflect the energy poverty situation of each province [59]. The advantage of this method is that it considers not only the impact of expenditure on energy demand but also the impact of other exogenous factors. Due to the great differences in regional development in China, this paper measures the energy poverty lines of the eastern, central, and western regions, respectively.

The basic form of the energy poverty line is shown in Eq. (4):

$$P_{\mathrm{mt}}Q_{\mathrm{nt}} = p_{\mathrm{mt}}q_{\mathrm{nt}} + \beta_{\mathrm{mt}}\left(I_{\mathrm{mt}} - \sum\nolimits_{n=1}^{k} p_{\mathrm{nt}}q_{\mathrm{nt}}\right), \quad (4)$$

where p_{mt} and p_{nt} represent the prices of the m th and n th commodities, respectively. Q_{nt} denotes the demand for the n th commodity. q_{mt} and q_{nt} denote the basic demand of the m th and n th commodities, respectively. I_{mt} represents per capita disposable income. β_{mt} stands for marginal propensity to consume. The above commodity types are considered as energy commodities in this paper. Equation (4) is converted into

$$P_{mt}Q_{mt} = p_{\mathrm{mt}}q_{\mathrm{mt}} - \beta_{\mathrm{mt}}\sum\nolimits_{n=1}^{k} p_{\mathrm{nt}}q_{\mathrm{nt}} + \beta_{\mathrm{mt}}I_{\mathrm{mt}} \quad (5)$$

Because $p_{\mathrm{mt}}q_{\mathrm{mt}}$ and $\sum_{n=1}^{k} p_{\mathrm{nt}}q_{\mathrm{nt}}$ are constant terms, Eq. (5) is converted into

$$P_{\mathrm{mt}}Q_{\mathrm{mt}} = \alpha_{\mathrm{mt}} + \beta_{\mathrm{mt}}I_{\mathrm{mt}} + v_{\mathrm{mt}}, \quad (6)$$

where $P_{\mathrm{mt}}Q_{\mathrm{mt}}$ represents the energy consumption expenditures and α_{mt} and β_{mt} are the estimated regression coefficients of ordinary least square (OLS). Based on the theory of microeconomics, income is the basis of consumption, national income largely determines the size of national consumption, and there is a functional relationship between the two. The energy poverty line could be calculated through Eq. (6), that is, the basic demand of per capita energy consumption expenditure of households.

For the measurement of energy poverty intensity, apply Eq. (7):

$$EP_{mt} = \left|\frac{\mathrm{Expenditure}_{\mathrm{mt}} - \mathrm{Poverty\ line}_{m}}{\mathrm{Poverty\ line}_{m}}\right|. \quad (7)$$

Among them, $\mathrm{Expenditure}_{\mathrm{mt}}$ stands for per capita energy consumption expenditure. $\mathrm{Povertyline}_{m}$ stands for the energy poverty line. When it belongs to energy poverty, the intensity is the ratio of the energy consumption expenditure gap to the energy poverty line. When $\mathrm{Expenditure}_{\mathrm{mt}} = \mathrm{Poverty\ line}_{m}$, it means that the energy consumption expenditure gap is 0, which meets the basic needs of per a capita energy consumption expenditure of households, that is, there is no energy poverty.

Climate change This paper refers to the measurement methods of previous scholars [60, 61]. The temperature change formula of province (i) at time (t) is defined as follows:

$$CC_{it} = \frac{\mathrm{Temp}_{\mathrm{it}} - \mathrm{mean\ of\ Temp}_{t}}{\mathrm{Stand\ devation\ of\ Temp}_{t}}. \quad (8)$$

$\mathrm{Temp}_{\mathrm{it}} - \mathrm{mean\ of\ Temp}_{t}$ represents the difference between the temperature observed at time t in the province sample and the long-term average of each province. Stand devation of Temp_{t} represents the long-term standard deviation of each province. The measured values of climate change in this paper represent the standard deviation between the actual temperature and the historical average value of province (i) in time (t), which more truly reflects the changes of cold and hot temperatures.

Environmental regulation The previous literature mainly used proxy variables to measure environmental regulation, such as environmental pollution emissions, energy consumption per unit GDP, and other indicators to reflect the intensity of environmental regulation in various regions. Although this method could quickly compare the overall level of environmental regulation in various regions, it could not analyze the actual role and implementation effect of various environmental regulation tools. Most studies have different ways to measure the level of environmental regulation. In this paper, environmental regulation is defined as direct government intervention in environmental resources and, being the main feature of environmental regulation indicators, is mandatory in this paper. The environmental regulations discussed in this paper are related to mandatory regulations issued by the government. Therefore, considering the direct effect of environmental regulation tools, this paper measures environmental regulation from three dimensions: economic, legal, and supervised dimen-

Table 1 The definition of variables

Variable	Abbreviation	Measure	References
Explained variable			
Energy poverty	EP	$EP_i = \left\| \frac{Expenditure_i - Poverty\ line_i}{Poverty\ line_i} \right\|$	[59]
Explanatory variable			
Climate change	CC	$CC_{it} = \frac{Temp_{it} - mean\ of\ Temp_t}{Stand\ devation\ of\ Temp_t}$	[60, 61]
Economical environmental regulation	EER	Total investment proportion in environment pollution treatment	[62, 63]
Legal environmental regulation	LER	The number of penalty cases for environment	
Supervised environmental regulation	SER	The number of environmental protection agencies	
Control variable			
Gross domestic product	GDP	Ln (Gross Domestic Product)	[48, 64]
Urbanization rate	Urb	Ln (Urbanization rate multiplied by 100)	
Geographic location	Geo	North is 1, South is 0	[48]
Education	Edu	Ln (Average years of education)	[48, 64–66]
Population	Popu	Ln (Number of population)	

sions [62, 63]. The three types of environmental regulations (ER) are economic environmental regulation (EER), legal environmental regulation (LER), and supervised environmental regulation (SER). Firstly, EER is measured by the annual total government investment in environmental governance. Secondly, LER is measured by the number of environmental administrative punishment cases of enterprises at the end of the year. Thirdly, SER is measured by the number of environmental protection agencies at the end of the year.

Control variables Through sorting out and summarizing previous studies, EP and ER are also affected by other variables [48]. Therefore, the control variables selected in this paper include Gross Domestic Product (GDP), Urbanization rate (Urb), Geographic location (Geo), Education (Edu), and Population (Popu). This paper deals with the logarithm of control variables. GDP reflects the overall economic scale of a country or region. With rapid economic development, the living standards of the population rise, the consumption capacity increases, and energy efficiency improves, thus affecting the problem of energy poverty. Urbanization at higher levels can increase energy consumption through scale effects, such as by promoting economic growth, while simultaneously reducing it through technological and structural effects [64]. Since this study includes the relationship between climate change and energy poverty, the climatic differences between the North and the South are more pronounced, and geographic location presents different levels of economic scale and energy structure in China, which affects energy poverty [65]. Increasing levels of education and population quality may affect residential income and energy efficiency, thereby affecting energy poverty [66]. Therefore, all of the above variables affect energy poverty to some extent and are used as control variables in this paper.

Table 1 illustrates the definition of all variables. Among them, the measurement method of energy poverty (EP) has been explained above.

Descriptive statistics of variables

Table 2 shows the descriptive statistics of all variables. The minimum value of energy poverty intensity is 0, and the maximum value is 0.642. This shows that there are both energy poverty areas and non-energy poverty areas. Due to the diversity of climate types in China, the seasonal temperature difference is obvious in different regions. In addition, the regulatory effect of environmental regulations varies greatly among different provinces.

Table 2 The descriptive statistics of variables

Variable	Obs	Mean	Std. Dev	Min	Max
EP	480	0.049	0.122	0	0.642
CC	480	3.538	1.401	1.745	26.93
EER	480	7.631	1.313	2.079	10.95
LER	480	5.879	0.760	3.258	7.041
SER	480	5.000	0.983	1.668	6.859
GDP	480	9.423	1.014	6.213	11.62
Urb	480	3.972	0.249	3.291	4.545
Geo	480	0.500	0.501	0	1
Edu	480	2.177	0.115	1.853	2.548
Popu	480	8.184	0.748	6.297	9.443
CC*EER	480	27.15	13.08	5.516	237.8
CC*LER	480	20.82	9.151	3.695	166.7
CC*SER	480	17.78	8.181	2.164	138.6

$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$

Results

Data sources

During the "Tenth Five-Year Plan" period, China has made significant progress in the construction of renewable energy laws and regulations and has gradually improved the policies supporting the development of renewable energy, creating a favorable legal and policy environment for accelerating the development of renewable energy. On February 28, 2005, the *Renewable Energy Law* was promulgated. In order to establish a better measuring system on the impact of environmental regulation on energy property, this paper selects the statistical data of 30 provinces in China from 2005 to 2020, with a total of 480 samples. The explained variable EP stems from WIND and the *Provincial Statistical Yearbooks*. The explanatory variable CC derives from the *National Centers for Environmental Information* (NCEI). The three types of environmental regulations EER, LER, and SER are from *China Statistical Yearbook on Environment*, whereas the control variables GDP, Urb, Geo, Edu, and Popu are from the *China Statistical Yearbook*. Considering the availability of data, Tibet, Hong Kong, Macao, and Taiwan are excluded. The empirical software used in this paper is Stata [16].

Identification of the energy poverty

Household energy consumption expenditure includes oil expenditure, natural gas expenditure, electricity expenditure, and other energy expenditures [67]. Due to the large differences in regional development in China, there are large differences in regional development, and resident's energy usage varies significantly in different regions, whereas the use of a uniform energy poverty line cannot accurately determine the Energy poverty level [65]. Therefore, the energy poverty lines are measured in this paper within three regions: the east, the center, and the west. According to Eq. (6), the estimated results are shown in Table 3.

By measuring the basic demand of residents' energy consumption expenditure in the whole country and regions, Table 3 shows that the national energy consumption poverty is 492.545 yuan per year. The energy consumption poverty in the eastern, central and western regions is 570.671, 475.719, and 394.013, respectively. Among them, the poverty of energy consumption in the central region is closer to the national level. The energy consumption poverty in the eastern region is higher than that in the whole country, and the energy consumption poverty in the western region is lower than that in the whole country. In addition, there are subtle differences in gas and other energy expenditures in the eastern, central, and western regions. However, the oil expenditure factor in the western region is 56.017, which is significantly lower than that of the eastern and central regions. The electricity expenditure coefficient in the eastern region amounted to 200.174, which is significantly higher than that of the central and western regions. As the level of economic development, income, and education in the eastern region is higher than that in the central and western regions, residents in the eastern region are better able to consume high-quality energy. However, due to the weak energy infrastructure, residents in the western region experience relatively lower income and education level, resulting in a lower basic demand for energy consumption expenditure. It could be seen that residents' energy consumption expenditure varies greatly in different regions, and the energy poverty level in the central region is closer to the whole country.

Table 3 Identification of the energy poverty

Parameter	'Total		East		Central		West	
	α_i	β_i	α_i	β_i	α_i	β_i	α_i	β_i
Oil	78.063***	0.15***	107.134***	0.12***	94.998***	0.097***	56.017***	0.093***
	(11.084)	(0.042)	(13.79)	(0.014)	(19.894)	(0.011)	(15.631)	(0.009)
Natural gas	56.017***	0.03***	74.063***	0.03***	46.061***	0.028***	44.044**	0.062***
	(8.0045)	(0.006)	(13.308)	(0.004)	(10.219)	(0.003)	(21.464)	(0.014)
Electricity	176.186***	0.109***	200.174***	0.095	145.673***	0.106***	128.091***	0.107***
	(17.299)	(0.008)	(14.204)	(0.005)	(17.101)	(0.017)	(19.493)	(0.032)
Other	182.279***	−0.037	189.3***	−0.011	188.987***	0.017***	165.861***	0.041***
	(11.127)	(0.005)	(11.098)	(0.004)	(28.212)	(0.0015)	(28.076)	(0.014)
Total	492.545	0.252	570.671	0.234	475.719	0.248	394.013	0.303

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Table 4 The impact of CC on EP

Variable	Group 1		Group 2	
	FE	GMM	FE	GMM
CC	0.0271**	0.0459**	0.0248***	0.0403*
	(2.63)	(2.06)	(3.33)	(1.73)
GDP			– 0.4616***	– 0.5359***
			(– 2.95)	(– 2.64)
Urb			– 0.2585	– 0.7111
			(– 1.00)	(– 0.40)
Geo			– 0.0961***	– 0.9406
			(– 2.97)	(– 0.21)
Edu			0.6977	2.2517***
			(0.47)	(2.65)
Popu			0.5625*	0.3729*
			(1.95)	(1.97)
Cons	0.1018**	0.0234	– 0.5873	0.4516
	(2.15)	(1.29)	(– 0.91)	(– 1.07)
R^2	0.7532		0.6793	
Hansen		0.837		0.851
Hausman	28.09***		24.95***	
AR (1)		0.026		0.025
AR (2)		0.331		0.197
Observation	480	480	480	480

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

The impact of CC on EP

From the results shown in Table 4, the regression results for EP are shown in Group 1 excluding control variables and Group 2 including control variables. Firstly, for FE, the regression coefficient for CC in Group 1 is 0.0271 at a significant level of 5%. For sys-GMM, the regression coefficient for CC is 0.0459, which is at the 5% significant level. This indicates that CC is positively correlated with EP without control variables. Secondly, Group 2 added control variables. For FE, the regression coefficient for CC is 0.0248, which is at the 1% significant level. For sys-GMM, the regression coefficient for CC is 0.0403 at a significant level of 10%. It shows that CC still has a positive effect on EP after adding control variables. This may be attributed to the fact that most area of China are temperate, leading to an increase in the use of heating equipment by residents during cold winter. The hot summer may cause residents to increase the usage rate of air conditioning cooling. Then the consumption of energy sources such as electricity and natural gas would increase, the per capita disposable income of residents would be relatively stable in the short term; thus, the incidence of energy poverty may be increased. The coefficients of GDP and Urb are both negative, which has negative impacts on EP. The improvements of economic development and urbanization are conducive to alleviating energy poverty. Moreover, the factors of geographical location would have a certain impact on energy poverty, so Geo is introduced as a control variable in this paper. Energy poverty is alleviated to some extent by the widespread adoption of collective heating in the north during winters, which can improve energy efficiency and save costs, but there is no collective heating in the south, which increases the pressure on energy consumption. In addition, the Hausman results for Groups 1 and 2 are 28.09 and 24.95, respectively, at the 1% significance level.

The impact of ER on EP

The regression results of the three types of ER for EP are shown in Table 5. With the addition of control variables, Groups 1, 2, and 3 exhibit regression results for EER, LER, and SER, respectively. In Group 1, the regression coefficients for FE and sys-GMM for EER are 0.023 and 0.0121, respectively. However, for FE, the regression coefficient for LER in Group 2 is -0.047, which is not significant. For sys-GMM, the regression coefficient for LER of −0.5419 reaches a significant level of 1%. In Group 3, the regression coefficient for SER amounted to -0.0287 for FE and for sys-GMM, the regression coefficient for SER reaches −0.1232, which is significant at the 5% level.

It shows that EER is positively correlated with EP, which may increase the incidence of energy poverty to a certain extent. However, LER and SER have significant negative effects on EP and may be effective in alleviating energy poverty. On one hand, this may be attributed to the government's strengthened supervision of enterprise production, aimed at stimulating green innovation of enterprises and improving output level and energy efficiency. On the other hand, the distribution of energy resources among residents is more reasonable; thus, the incidence of energy poverty could be reduced. However, the increase of government investment in environmental governance may affect the income and employment level of residents. With the uncertainty of economic policies, the negative effect of employment on energy poverty would be more obvious. Hausman results shown in Groups 1, 2, and 3 are 23.77, 17.85, and 20.76, respectively, at the 1% significance level.

Furthermore, given the uncertainty of a realistic situation, ensuring an efficiency of environmental regulation often relies on a comprehensive consideration of environmental regulation. Based on this background, this paper further analyzes the interaction of different types of environmental regulation in Table 6. According to Table 6, the EER*LER has a significant inhibitory effect on EP and for GMM, the regression coefficient for EER*LER in Group 1 amounted to -0.068, whereas for FE, the coefficient of 0.00178 is not significant. In addition, EER*SER, LER*SER, and EER*LER*SER have significant negative

Table 5 The impact of ER on EP

Variable	Group 1		Group 2		Group 3	
	FE	GMM	FE	GMM	FE	GMM
EER	0.023	0.0121***				
	(1.05)	(3.47)				
LER			– 0.047	– 0.5419**		
			(– 0.69)	(– 2.56)		
SER					– 0.0287	– 0.1232**
					(– 0.47)	(– 2.12)
GDP	– 0.435***	– 0.603**	– 0.4185***	– 0.2685	– 0.3975**	– 0.4789
	(– 2.84)	(– 2.52)	(– 2.89)	(– 0.07)	(– 2.59)	(– 0.65)
Urb	– 0.5158	– 0.5341**	– 0.4710	– 1.0717***	– 0.4590	– 0.4891**
	(– 0.95)	(– 2.13)	(– 0.88)	(– 2.94)	(– 0.85)	(– 2.34)
Geo	– 0.1372***	– 0.4718*	– 0.0919**	– 0.2726	– 0.1006**	– 0.1811
	(– 2.60)	(– 1.90)	(– 2.00)	(– 0.01)	(– 2.50)	(– 1.15)
Edu	0.6875	2.2611***	0.2278	1.1279*	0.1908	2.0736***
	(0.47)	(2.78)	(0.39)	(1.74)	(0.32)	(3.02)
Popu	0.5504*	0.5838	1.2598*	0.7205	1.253*	0.6612
	(1.67)	(0.97)	(1.86)	(1.54)	(1.85)	(0.57)
Cons	– 0.449	– 1.5466	– 4.5164	1.9539	– 4.7568	– 2.5673
	(– 0.68)	(– 0.74)	(– 0.78)	(1.10)	(– 0.82)	(– 0.33)
R^2	0.6634		0.6318		0.6419	
Hansen test		0.152		0.140		0.204
Hausman test	23.77***		17.85***		20.76***	
AR (1)		0.005		0.020		0.039
AR (2)		0.271		0.292		0.178
Observation	480	480	480	480	480	480

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

effects on EP, and the effect of LER*SER is most prominent where the regression coefficient is -0.199 at a significant level of 1%. This means the coordination of different environmental regulations helps alleviate energy poverty, especially the combination of law and supervision.

The moderating effect of ER

The regression results of the CC and ER crossover terms for FE and sys-GMM on EP are shown in Table 7. Under the premise that the control variables are introduced, Groups 1, 2, and 3 represent the moderating effects of EER, LER, and SER in the effect of CC on EP, respectively. In Group 1, the regression coefficient of CC for sys-GMM for EP of 0.1066 is significant at the 5% level. EER's sys-GMM regression coefficient of 0.0449 is significant at a level of 1%. However, for FE, the regression coefficient of CC*EER amounted to – 0.0094 at a significant level of 1%. For sys-GMM, the regression coefficient of CC*EER is – 0.0082, which is significant at the 5% level. This shows that CC and EER have a positive effect on EP, but the regression coefficient of CC*EER to EP is negative. EER has a significant negative moderating effect, and the aggravating effect of CC on EP is decreasing.

However, in Group 2, the coefficients for CC and LER are 0.0249 and – 0.3819, respectively. The regression coefficients of CC*LER for FE and sys-GMM are 0.0051 and 0.0006, respectively. This shows that LER has a positive moderating effect in the process of CC aggravating EP. In Group 3, the sys-GMM coefficient for CC is 0.0548 at the 10% significance level and the regression coefficient for SER is – 0.0805, but the result is not significant. The regression coefficient of CC*SER for FE amounts to 0.0016, which is significant at the 10% level. This shows that CC is positively correlated with EP, and the regression coefficient of CC*SER is also positive. SER has a positive moderating effect in the process of CC exacerbating EP. It indicates that EER has a significant negative moderating effect in CC affecting EP. LER and SER have positive moderating effects, but they have a direct effect on the suppression of EP. As EER may promote the government's alleviation policy for energy poverty, promote the use of clean energy, and improve the ecological environment and climate change, this is likely to have a positive

Table 6 The interaction of different types of ER

Variable	Group 1		Group 2		Group 3		Group4	
	FE	GMM	FE	GMM	FE	GMM	FE	GMM
EER*LER	0.00178	– 0.068*						
	(0.62)	(– 1.87)						
EER*SER			– 0.000206	– 0.0571**				
			(– 0.05)	(– 2.26)				
LER*SER					– 0.0126**	– 0.199***		
					(– 2.11)	(– 2.90)		
EER*LER*SER							– 0.000632	– 0.00588***
							(– 1.29)	(– 4.39)
GDP	– 0.430***	0.011	– 0.424***	– 0.379	– 0.346***	1.367	– 0.397***	– 1.189***
	(– 4.90)	(0.02)	(– 2.87)	(– 0.56)	(– 3.64)	(1.33)	(– 4.39)	(– 3.32)
Urb	– 0.501*	– 9.860***	– 0.477	– 5.452	– 0.389	– 2.619	– 0.400	3.786***
	(– 1.75)	(– 2.79)	(– 0.90)	(– 1.07)	(– 1.36)	(– 0.44)	(– 1.38)	(3.29)
Geo	– 0.055	– 1.448**	– 0.078*	– 0.653	– 0.038	0.458	– 0.029	– 0.211
	(– 1.55)	(– 2.01)	(– 1.89)	(– 0.70)	(– 0.98)	(0.38)	(– 0.73)	(– 0.65)
Edu	0.244	14.104***	0.222	13.46**	0.129	– 0.0298	0.156	– 1.866**
	(0.50)	(3.03)	(0.38)	(2.07)	(0.27)	(– 0.00)	(0.32)	(– 2.32)
Popu	1.227***	– 1.768	1.262*	– 0.211	1.226***	0.119	1.321***	1.696*
	(3.52)	(– 1.15)	(1.84)	(– 0.11)	(3.56)	(0.09)	(3.79)	(1.85)
							(– 1.29)	(– 4.39)
_cons	– 4.409	20.068	– 4.711	0.277	– 4.936	2.390	– 5.476*	– 11.99
	(– 1.45)	(1.36)	(– 0.81)	(0.01)	(– 1.64)	(0.19)	(– 1.78)	(– 1.52)
R^2	0.472		0.472		0.477		0.474	
Hansen test		0.313		0.154		0.177		0.466
Hausman test	34.35***		18.24***		20.41***		17.91***	
AR (1)		0.015		0.021		0.022		0.079
AR (2)		0.597		0.804		0.744		0.700
Observation	480	480	480	480	480	480	480	480

***p < 0.01, **p < 0.05, *p < 0.1

impact on the achievement of the goals of energy poverty reduction. LER and SER could come with a "cost of compliance." In other words, government environmental regulations may raise the cost of corporate pollution control. When enterprises focus on how to avoid government penalties, it would have a crowding out effect on the input and output of energy reform of enterprises, and would increase the incidence rate of energy poverty.

Results of a robust test

As this paper considers the impact of environmental regulations and energy poverty, the robust test is carried out for the part of all years in the full province samples [68, 69]. All province samples data from 2011 to 2020 are taken as new subjects, and the results of the regression are shown in Table 8.

1. For EER, as shown in Group 1, the influence coefficient of CC on EP amounts to 0.455, which is significant at the 1% level. The regression coefficient of EER of 0.003 is significant at the 1% level. The influence coefficient of CC*EER on EP is – 0.0071 and is significantly negative at the 1% level. This shows that the moderating effect of EER is negative significantly, inhabiting the positive impact of CC on EP.
2. For LER, as shown in Group 2, the influence coefficient of CC of 0.0493 is significant at the 5% level, but the influence coefficient of LER is – 0.01537. The influence coefficient of CC*LER on EP of 0.0063 is significant at the level of 5%. This indicates that LER has a positive moderating effect.
3. For SER, as shown in Group 3, the regression coefficient for CC is 0.0025 and the regression coefficient for SER is – 0.0038, whereas the regression coefficient of TS*SER of is significant at 0.0003 and at the 1% level. This shows that SER also has a positive

Table 7 The moderating effect of ER in the impact of CC on EP

Variable	Group 1		Group 2		Group 3	
	FE	GMM	FE	GMM	FE	GMM
CC	0.0534	0.1066**	− 0.0055*	0.0249*	0.0176*	0.0548*
	(0.57)	(2.22)	(− 1.78)	(1.91)	(1.66)	(1.75)
EER	0.0289	0.0449***				
	(0.62)	(2.66)				
LER			− 0.1503***	− 0.3819*		
			(− 6.33)	(− 1.74)		
SER					− 0.0446	− 0.0805
					(− 0.08)	(− 1.53)
CC*EER	− 0.0094***	− 0.0082**				
	(− 3.41)	(− 5.15)				
CC*LER			0.0051***	0.0006*		
			(2.64)	(1.92)		
CC*SER					0.0016*	− 0.0037
					(1.65)	(− 1.30)
GDP	− 0.4717	− 0.7562***	− 0.4015	− 0.5274	− 0.4163***	− 0.5568*
	(− 0.76)	(− 4.23)	(− 0.76)	(− 0.19)	(− 3.06)	(1.75)
Urb	− 0.3179***	− 0.1651*	− 0.3333***	− 0.8834*	− 0.266	− 0.2981
	(− 4.21)	(− 1.90)	(− 4.45)	(− 1.80)	(− 1.19)	(− 0.34)
Geo	− 0.1243*	− 0.0934	− 0.0738	− 0.0783	− 0.0790**	− 0.0406
	(− 1.91)	(− 1.30)	(− 0.59)	(− 1.12)	(− 2.06)	(− 0.46)
Edu	0.7254**	2.8096***	0.4948	2.6344	0.6571**	2.3821*
	(2.29)	(2.92)	(1.23)	(0.53)	(2.39)	(1.77)
Popu	0.5217*	0.9277	0.6083***	1.0101**	0.552**	0.8293***
	(1.76)	(1.42)	(2.86)	(2.39)	(2.14)	(2.72)
Cons	− 0.1854*	− 6.1643	0.0828***	− 3.1482***	− 0.5977	− 5.0419
	(− 1.95)	(− 0.21)	(3.40)	(− 2.71)	(− 0.83)	(− 1.40)
R^2	0.6715		0.6665		0.6645	
Hansen test		0.914		0.897		0.921
Hausman test	32.31***		25.00***		27.51***	
AR (1)		0.026		0.017		0.041
AR (2)		0.251		0.179		0.108
Observation	480	480	480	480	480	480

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

regulating effect. Thus, the basic conclusions of this paper are robust.

Discussion

The results are discussed as follows (see Fig. 2): The CC has a positive correlation with EP, that is, the impact of climate change would increase the incidence of energy poverty, which is consistent with Feeny et al. [10] and Li et al. [22]. Due to the deterioration of the external climate environment, the government adjusts the energy use structure through policy tools, resulting in energy poverty. At the same time, it may also hinder crop production, reduce farmers income, and increase energy poverty. Secondly, EER has a positive correlation with EP, whereas LER and SER have negative correlations with EP, the same has been found by Andrieu et al. [28] and Tang et al. [29] and shows that economic environmental regulation would affect the fluctuation of energy prices, increase the energy consumption burden of residents, and thus exacerbate energy poverty.

However, the difference is that the regression coefficient of CC*EER is negative, while the regression coefficients of CC*LER and CC*SER are positive. The economic environmental regulation has a significantly

Table 8 The results of the robust test

Variable	Group 1 GMM	Group 2 GMM	Group 3 GMM
CC	0.455***	0.0493**	0.0025***
	(4.64)	(2.07)	(3.83)
EER	0.003***		
	(3.49)		
LER		– 0.01537	
		(– 0.46)	
SER			– 0.0038**
			(– 2.21)
CC*EER	– 0.0071***		
	(– 4.47)		
CC*LER		0.0063**	
		(– 1.70)	
CC*SER			0.0003***
			(3.91)
GDP	– 0.2762	– 0.3457	– 0.0842
	(– 0.12)	(– 1.31)	(– 0.96)
Urb	– 1.5719**	– 1.0524	– 0.2289
	(– 2.07)	(– 0.31)	(– 0.29)
Geo	– 0.2158*	– 0.2121	– 2.763
	(– 1.93)	(– 1.44)	(– 0.77)
Edu	4.104**	3.3688***	2.857***
	(2.20)	(2.79)	(2.93)
Popu	0.0312	0.0896	– 0.2936
	(0.60)	(0.72)	(0.22)
Cons	– 0.384	– 0.8247	3.6842
	(– 1.44)	(– 0.26)	(0.44)
Hansen test	0.935	0.912	0.941
AR (1)	0.023	0.084	0.046
AR (2)	0.355	0.194	0.246
Observation	300	300	300

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

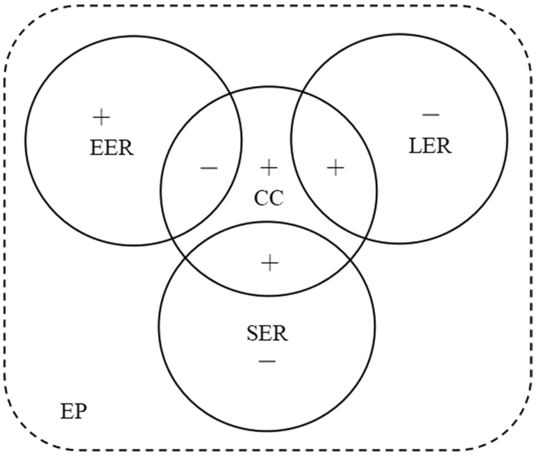

Fig. 2 The influence of CC and ER on EP

negative moderating effect, while the legal and supervised environmental regulations have a positive moderating effect, and would aggravate the positive impact of CC on EP. This is consistent with Ma et al. [44], who believed that the government's strict legal constraints and supervision of green production within enterprises might aggravate the energy poverty of low-income families. According to the "green paradox," this in turn may exacerbate climate degradation and environmental pollution, forming a vicious circle.

Conclusions and policy implications

The conclusions are as follows: First, the climate change increases energy poverty, that is, in cold winters, the energy demand for heating is increased, while in hot summers, the energy demand for cooling is increased. Since income and energy supply remain stable in the short term, the climate change has exacerbated energy poverty. Second, the economical environmental regulation increases energy poverty, while the legal and supervised environmental regulations are the opposite. With the increase of economic policies uncertainty, the negative impact of economical environmental regulation on energy poverty will become more prominent. However, the legal and supervised environmental regulations improve the technology level and energy efficiency of enterprises, promote reasonable distribution of resources, which may reduce the energy poverty. In addition, the interaction of different types of environmental regulation shows that it helps alleviate energy poverty. Third, the economical environmental regulation has a negative moderating effect, while the legal and supervised environmental regulations have positive moderating effects, which indicates that the economical environmental regulation may promote the government's energy subsidy policies, increase the use of clean energy, improve the ecological environment, and mitigate climate change, and to some extent curb the occurrence of energy poverty. However, the legal and supervised environmental regulations may increase the pollution control cost of enterprises, produce a crowding out effect on production and investment, and increase the incidence of energy poverty. Finally, the national basic energy poverty line is lower than that in the eastern region, higher than that in the western region, and close to that in the central region, which reflects the heterogeneity of energy poverty in different regions of China.

Based on the above conclusions, the policy implications are as follows: First of all, it is necessary to start from the product market, rely on the innovative drive to improve the performance of energy-saving products, and reduce the energy consumption unit time and the energy poverty caused by the increase of energy payment costs. The environmental protection department should vigorously promote green buildings, maximize the use of natural energy, reduce environmental damage and pollution, and achieve zero fossil energy.

Furthermore, for the energy poverty caused by the different environmental regulation, the government should focus on overcoming income problems. According to the energy gradient theory, the income level determines the amount of energy demand and consumption structure of households and enterprises. Increasing employment and enterprises' green technological innovation capacity is conducive to improving the disposable income of households and enterprises, thereby improving the abilities to pay for energy and reducing energy poverty. In addition, the government is the leader of environmental policy, which can regulate the resource allocation of households and enterprises by promoting modern clean energy and performing the necessary public service functions.

Last but not least, since the significant differences in economic levels and energy consumption in different regions of China, the government should rationally use various environmental regulations to improve energy efficiency and transform the economic growth. Specifically, for the eastern region with high energy consumption level, it is necessary to adjust the industrial structure and energy consumption structure, and further promote the development model of low-carbon economy. Likewise, the central region should improve carbon productivity and promote the construction of a new energy industry. Moreover, the western regions which have low energy consumption levels could develop resource-saving and environment-friendly industries with distinctive advantages and enhance the sustainability of economic development to achieve a win–win result of economic growth and ecological protection.

The limitations of this paper are as follows: First, the non-linear impact of climate change on energy poverty is not examined. Second, the threshold effect of environmental regulation is not taken into account. Further research will use the panel threshold regression model, taking climate change as the threshold variable, to investigate the non-linear impact of climate change in different regions on energy poverty. Moreover, it is advised to take environmental regulation as the threshold variable, to further investigate the moderating effect of environmental regulation in the impact of climate change on energy poverty. In addition, other variables such as humidity can also be introduced on the basis of temperature to comprehensively and systematically measure climate change.

Author contributions

Z.T.: conceptualization; project administration; resources; methodology. Y.C.: original writing; investigation; data curation; resources. Z.W.: formal analysis; project administration; review and editing. C.D.: investigation; data curation; software. All authors reviewed the manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Written informed consent was obtained from authors for publication of this paper and any accompanying tables. A copy of the written consent is available for review by the Editor of this journal.

Competing interests

The authors declare no competing interests.

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