Clean energy diffusion and energy poverty alleviation

Abstract

Eliminating energy poverty is an important part of the United Nations Millennium Development Goals. While clean energy technology is considered to be an important means to alleviate energy poverty. Existing research pays less attention to the relationship between the two. This study measures the diffusion of clean energy technology with patent citation information, and conducts research based on balanced panel data of 30 provinces in China from 2004 to 2019. The results show that the diffusion of clean energy technology can not only directly achieve energy poverty reduction, but also indirectly alleviate energy poverty by improving energy efficiency and employment. However, such positive role of technology on poverty is affected by human capital. When the number of college students per 10,000 people in each province exceeds 179, energy poverty can be alleviated by technology diffusion. At the same time, the mitigation effect also varies greatly due to different technologies and regions. Among them, technology sourced from developed economies such as the United States, Japan and the European Union has a greater role than domestic technology. Meanwhile, the effect of energy poverty reduction is more significant in the eastern region, high-income areas and low-energy poverty areas than others in China. Based on the above findings, we propose policy recommendations to alleviate energy poverty by promoting the diffusion of clean energy technologies.

Keywords: Energy poverty, Clean energy, Technology diffusion, Threshold regression model.

1 Introduction

As one of the signs of poverty in developing countries, energy poverty is highly concerned by international organizations such as the World Bank, the International Energy Agency (IEA) and the United Nations. Affordable, reliable and sustainable modern energy supply has always been an important goal of human development. Although the world has made great progress in energy development, utilization and popularization, regional and local energy shortages are still widespread. According to the report of the International Energy Agency (IEA), in 2019, the proportion of clean energy in final energy consumption accounted for only 17.7% (IEA,2022). As of 2020, 733 million people worldwide still do not fully solve their electricity problems, and 2.4 billion people do not have access to clean cooking fuel and technology(IEA,2020). Energy shortage and the resulting poverty (Nguyen and Nasir, 2021),education (Zhang et al., 2021), health (Lacey et al., 2017),social equity (Dong et al., 2022a) and ecological environment (Wang et al., 2015) are still important constraints on social development in some developing countries and economically backward regions.

China is the largest developing country in the world, and it is also facing more severe and complex energy poverty. The proportion of energy poverty in China is 18.9%, and 46% of energy poverty households lack modern energy and cannot meet basic electricity needs (Lin and Wang, 2020). At the same time, China 's total energy is abundant, but the distribution of resources is uneven. The per capita resources of coal, oil and natural gas are only 1/2, 1/15 and 1/15 of the world average[1]. Although China achieved the goal of 100% electricity access by 2015, about 75% of rural households still use solid fuels such as wood and coal for cooking (Tang and Liao, 2014). The use of traditional solid fuels has caused serious harm to the health of residents. 10.79% of rural residents in China die from respiratory diseases (Hong, 2022). If rural residents can give up traditional biomass energy[2] and use clean energy, the probability of children and adults suffering from respiratory diseases will be reduced by 80% and 45% respectively (Staff Mestl et al., 2006).

With the shortage of global fossil energy supply and the grim situation of climate change, countries around the world have realized the importance of developing clean energy. In particular, China is in a critical period of economic development and low-carbon transformation. The 20th National Congress of the Communist Party of

[1] China 's Energy Situation and Policy White Paper. (http://www.scio.gov.cn/zxbd/nd/2007/document/310015/310015_2.htm)

[2] e.g., wood, animal waste and crop waste.

China pointed out that it is necessary to promote clean, low-carbon and efficient use of energy and accelerate the planning and construction of a new energy system. In order to achieve the goal of achieving carbon peak by 2030 and carbon neutrality by 2060, and to transition to a sustainable development model. The proportion of China 's coal energy in the allocation will decrease from 60% in 2017 to 35% in 2040[3], and the use of energy will be more intense. The diffusion of clean energy technology provides a huge opportunity to promote the use of modern energy and solve the problem of energy shortage.

With the global diffusion of new technologies, adopting new technologies that include existing clean energy rather than inventing new technologies has become an important means to improve performance and save time (Ejemeyovwi et al., 2018). Therefore, the technology acceptance model has been widely discussed (Chen et al., 2017; Davis, 1989; Kardooni et al., 2016). Studies have shown that the adoption of clean energy technologies is of great significance for improving energy consumption structure, ensuring energy security and reducing carbon emissions (Liao, 2021). Scholars use the proportion of clean energy in total energy production to measure the promotion and use of clean energy, confirming that the development of clean energy can reduce the possibility of respondents falling into energy poverty (Hong, 2022). Furthermore, the study makes it clear that in an economy, the higher the adoption and penetration of digital technologies, the smaller the dependence on fossil energy and the demand for electricity generation, thus playing an active role in curbing energy poverty (P. Wang et al., 2022). At the same time, some scholars have noticed the important role of renewable energy technology innovation in energy poverty alleviation (W. Wang et al., 2022), but they have not further considered the impact of technology diffusion. At present, there is still a lack of empirical evidence on whether and how the diffusion and adoption of low-carbon technologies can alleviate energy poverty.

Therefore, based on the above theoretical analysis, this paper uses the patent information of low-carbon technology and the energy poverty index based on macro

[3]The International Energy Agency (IEA) has published data.

provincial data to empirically analyze the mechanism of clean energy technology diffusion on China 's energy poverty. Compared with previous studies, the research contributions are mainly reflected in the following three points: First, this paper links the diffusion of energy technology and energy poverty for the first time, and comprehensively analyzes the impact of clean energy technology diffusion on energy poverty reduction. Secondly, this paper deeply discusses the possible role of energy efficiency, employment and human capital in the process of the impact of clean energy technology diffusion on energy poverty, enriches the relevant theories of the relationship between low-carbon technology diffusion and energy poverty, and provides important empirical evidence reference for the formulation and implementation of China 's energy poverty alleviation policy. Thirdly, unlike previous studies that only use subjective data to measure technology, this paper innovatively uses the objective data of clean energy patent citation information to measure the diffusion and adoption of clean energy technology. Patent citation information contains the record of latecomers learning from existing inventions, which is more scientific and reasonable. At the same time, we identify the sources of technology diffusion and adoption, and divide them into five regions: China, the United States, Europe, Japan and South Korea, and explore the different effects of clean energy technology diffusion in different countries on alleviating China 's energy poverty.

The rest of this article is structured as follows. Section 2 summarizes the relevant literature review. Section 3 puts forward the research hypothesis. Section 4 builds an empirical model and introduces the data. Section 5 analyzes the specific empirical results. Section 6 summarizes the conclusions and provides policy recommendations.

2 Literature review

2.1 The measurement of energy poverty

The measurement methods of energy poverty mainly include single index method and multidimensional energy poverty index method. Among them, the single index method mainly refers to the use of an indicator or measure a specific aspect to evaluate the degree of energy poverty. The 10% Indicator proposed by Boardman (1991) is the earliest energy poverty measurement method in the world. If household energy consumption exceeds 10% of household disposable income, it is an energy poor household. Subsequently, the 10% Indicator was used to measure Britain 's energy poverty. Healy and Clinch (2004) conducted a survey of 1,500 households in Ireland and found that the 10 % index method cannot accurately measure the energy poverty status of the country due to the economic development of the two countries and inconsistent energy prices. Hills (2011) defined high energy consumption level and low income level as the Low Income High Costs (LIHC) Approach. Compared with the 10% indicator, this method excludes the influence of high income and high consumption groups. However, the Low Income High Costs (LIHC) Approach ignores all vulnerable groups such as the elderly, children and the disabled (Middlemiss, 2017).

Therefore, more and more scholars consider energy poverty from a multidimensional perspective. Wang et al. (2015) creatively constructed an energy poverty comprehensive evaluation system including nine indicators. It is also found that China 's energy poverty gradually eased in the 12 years from 2000 to 2011, and showed obvious regional heterogeneity. Sadath and Acharya (2017) used the multidimensional energy poverty index method to analyze the 2011 and 2012 Indian Human Development Survey (IHDS-II) data, and found that energy poverty is widespread in India. Sokołowski et al. (2019) considered five aspects of energy poverty, and used the multidimensional energy poverty index method to calculate that 10% of Poland 's households are in energy poverty. Through the above research, it can be found that although many scholars have measured energy poverty, there is no uniform standard for the measurement of energy poverty.

2.2 The impacts and determinants of energy poverty

In recent years, energy poverty has attracted more and more attention, and studies have found that it has a serious negative impact on economic growth, environment, education and health. Amin et al. (2020) examined the relationship between energy poverty and economic development in seven Southeast Asian countries from 1995 to

2017, and found that energy poverty was negatively correlated with long-term and short-term economic growth in selected countries. Specifically, a 1% increase in energy poverty reduces the level of economic development by 29.81%. In addition, energy poverty has led rural women and children to spend a lot of time collecting biomass fuel, unable to carry out productive work and education (Acharya and Sadath, 2019). At the same time, the use of traditional biomass energy increases carbon emissions (Zhao et al., 2021) and aggravates air pollution (Reyes et al., 2019). In such an environment, the harm of energy poverty to residents ' physical (Zhang et al., 2019) and psychological (Liddell and Guiney, 2015) is unavoidable

Therefore, how to accelerate energy poverty reduction has become one of the key issues that the government and society need to solve urgently. At present, relevant research mainly focuses on macro policy, energy structure transformation and social culture. Ma et al. (2022) found that strict environmental policies will lead to higher energy burdens for households using non-clean energy sources, and have less impact on households using clean energy. Hamed and Peric (2020) believed that the use and development of renewable energy can alleviate energy poverty and promote sustainable environmental development. This view has also been supported by Adom et al. (2021), Dong et al. (2021) and Zhao et al. (2022). Ampofo and Mabefam (2021) used the World Values Survey (WVS) data to measure religious beliefs in more than 100 countries, and the results showed that religious beliefs were positively correlated with energy poverty. Especially for families in developing countries and rural areas, religious activities exacerbate their energy poverty. In addition to the above factors, inclusive finance (Dong et al., 2022b) and digital economy (Qu and Hao, 2022) also help to alleviate energy poverty.

2.3 The role of energy technology diffusion and adoption in allevia ting energy poverty

As a follow-up process of technological innovation, technology diffusion and adoption have an important impact on promoting economic growth. Previous studies have shown that most technologies originated in developed countries and were first adopted at home, and then spread to countries with relatively backward economies (Comin and Hobijn, 2004). On the one hand, the positive externalities of technology diffusion can improve the efficiency of resource allocation through introduction, absorption and re-innovation, promote economic growth in poor areas, increase household income, and improve residents ' purchasing power of energy. On the other hand, technology diffusion can significantly improve the productivity of the clean sector. At the same time, the improvement of productivity can reduce the cost of clean energy (Bretschger et al., 2017) and promote the use of clean energy by residents, thus alleviating energy poverty. In addition, Rogers (2010) believed that innovative pioneers and early adopters will gain unexpected profits, thus widening the gap between the rich and the poor. Therefore, early adopters will become richer and richer, while late adopters will benefit less from innovation. Based on the above theoretical analysis, energy technology diffusion may be one of the effective ways to alleviate energy poverty, but there is no theoretical and empirical analysis of its energy poverty reduction effect.

3 Research hypothesis

Clean energy technology has been considered as an effective means to solve the problems of modern energy security (Aized et al., 2018), environmental pollution (Zhu et al., 2020) and energy shortage (W. Wang et al., 2022). For example, the substitution effect of clean energy technology in the development process can improve the environment by reducing the use of traditional energy, reducing carbon emissions, and promoting the transformation of energy structure (Dogan and Seker, 2016; Zoundi, 2017). Furthermore, Liao (2021) systematically analyzed 107 relevant literatures and found that the adoption of clean energy technologies in low-and middle-income countries (LMICs) can significantly have a positive impact on household welfare[4]. At the same time, researchers have also found that the adoption of digital technology and other new technologies can reduce power generation and energy consumption, thereby alleviating energy poverty (Lee and Shepley, 2020; P. Wang et al., 2022). According to this logic, the diffusion of clean energy technology can alleviate energy poverty more directly. This

[4]It includes education, environment, health, income and productivity and profitability.

leads to the following hypothesis:

H1: The diffusion of clean energy technology can alleviate energy poverty.

The International Energy Agency (IEA) believes that improving energy efficiency is the cheapest and cleanest way to meet basic energy needs. Improving energy efficiency, on the one hand, can produce energy-saving effects and reduce the basic energy demand of residents; on the other hand, it is conducive to saving energy production costs (Wang and Wang, 2020), reducing residents ' energy consumption expenditures, and reducing the burden of household energy consumption (Walker, 2008). In addition, improving energy efficiency can accelerate energy infrastructure and promote clean energy consumption such as natural gas, solar and wind energy. So as to optimize the energy consumption structure (Dong et al., 2018; Li and Lin, 2018) and improve the welfare of residents (Grey et al., 2017). Technology diffusion can reduce research and development costs and improve energy efficiency by promoting technological innovation (Chen et al., 2021). Therefore, one of the ways for clean energy technology diffusion to improve energy poverty may be the improvement of energy efficiency. This leads to the following hypothesis:

H1a: The diffusion of clean energy technologies alleviates energy poverty by improving energy efficiency.

Previous studies have found that women in energy-poor households spend a lot of time and cost on collecting biomass fuel (Acharya and Sadath, 2019), which deprives them of the opportunity to generate income for their families. The use of clean energy has greatly reduced their time to participate in housework and effectively promoted women 's employment (Hong, 2022). At the same time, the diffusion of clean energy technology can narrow the gap of research and development level between high-tech and low-tech companies, and increase the employment of low-tech companies. Thereby expanding employment opportunities for low-income people and alleviating the energy crisis of households. In addition, the study of Koomson and Churchill (2022) also found that employment precarity is positively related to energy poverty, and the resulting household financial difficulties will reduce the household 's ability to consume modern energy such as lighting and cooking, thus aggravating energy poverty. Based on the research on employment and energy poverty and clean technology diffusion and employment, it can be speculated that the diffusion of clean energy technology can alleviate energy poverty by promoting the employment of residents. This leads to the following hypothesis:

H1b: The diffusion of clean energy technologies alleviates energy poverty by increasing employment.

Technological innovation and diffusion is the main driving force and source of a country 's economic growth, and the level of human capital is an important factor affecting a country 's technological innovation and technological imitation and diffusion (Nelson and Phelps, 1966). The role of human capital in promoting technology diffusion has been repeatedly verified (Akhvlediani and Cieślik, 2020; Vandenbussche et al., 2006). For example, Gennaioli et al. (2013) used survey data including 110 countries to find that human capital plays an important role in regional innovation and dissemination. As a frontier low-carbon technology, clean energy technology has the characteristics of multi-objective, complex knowledge source and multi-dimension. Typical low-carbon technological innovation requires setting multiple goals such as production efficiency, production quality, and environmental labeling (Oltra and Saint Jean, 2009). Related to multi-objective, the development of low-carbon products is a more complex task, often in the early stages of the product life cycle, need to be away from the existing knowledge base of information and skills, the source of ideas is more complex (Braungart et al., 2007).Furthermore, due to the multi-dimensional and systematic characteristics of low-carbon technological innovation, knowledge exchange in low-carbon technological innovation is more important than general technological innovation (De Marchi, 2012). Therefore, clean energy technology generally has a higher entry threshold, and human capital can promote the technology spillover of foreign-funded enterprises to the host country, accelerate the speed of technology diffusion, and improve the host country 's ability to digest and absorb technology. This leads to the following hypothesis:

H2: Human capital plays a threshold role in the energy poverty reduction effect of the diffusion of clean energy technology.

4 Empirical model and data description

4.1 model specification

In order to verify H1, we use a two-way fixed effects model to discuss the impact of clean energy technology diffusion on energy poverty, as shown in Eq. (4.1):

$$\ln EP_{it} = \alpha_0 + \alpha_1 CET_{it} + \alpha_c X_{it} + \mu_i + \delta_t + \varepsilon_{it} \qquad (4.1)$$

Where, the dependent variable EP_{it} represents the energy poverty status of province i in year t, the core independent variable CET_{it} is the diffusion level of clean energy technology province i in year t, α1 represents the impact of clean energy technology diffusion on energy poverty, X_{it} represents the control variable, μ_i represents the individual fixed effect of province i that does not change with time, δ_i represents the fixed effect of control time, and ε_{it} represents the stochastic error term.

In order to verify Hypothesis 1a and Hypothesis 1b, namely to explore the possible mechanism of the diffusion of clean energy technology for energy poverty, according to the above, drawing on the practice of Zhao et al. (2022) and Hong (2022), whether energy efficiency and employment are its mediating variables, as shown in Eq. (4.2) and Eq. (4.3).

$$M_{it} = \beta_0 + \beta_1 CET_{it} + \beta_c X_{it} + \mu_i + \delta_t + \varepsilon_{it} \qquad (4.2)$$

$$\ln EP_{it} = \gamma_0 + \gamma_1 CET_{it} + \gamma_2 EI_{it} + \gamma_c X_{it} + \mu_i + \delta_t + \varepsilon_{it} \qquad (4.3)$$

Where, M_{it} is the mediating variable, including the energy efficiency and employment of province i in year t. In addition, in order to verify Hypothesis 2, on the basis of Eq. (4.1), we take the single threshold as an example to construct the following model:

$$\ln EP_{it} = \phi_0 + \phi_1 CET_{it} \times I(HUMAN \le \varphi) + \phi_2 CET_{it} \times I(HUAMN > \varphi) + \alpha_c X_{it} + \mu_i + \delta_t + \varepsilon_{it} (4.4)$$

Where, human is the threshold variable that is human capital, I (·) is the indicator function, and φ is the specific threshold value.

4.2 Data description

4.2.1 Dependent variable

Based on the research of Dong et al. (2022) and Zhao et al. (2021), this paper establishes a comprehensive energy poverty index composed of energy service availability, energy consumption cleanliness, energy management completeness, household energy affordability and energy efficiency. In order to compare the differences in energy poverty in various regions of China, we plotted provincial geographical distribution map of energy poverty (see Fig.1, Fig.2, Fig.3 and Fig.4). Overall, China 's energy poverty has been alleviated in recent years, but it still shows a distribution pattern of low in the south and the east, and high in the north and the west.

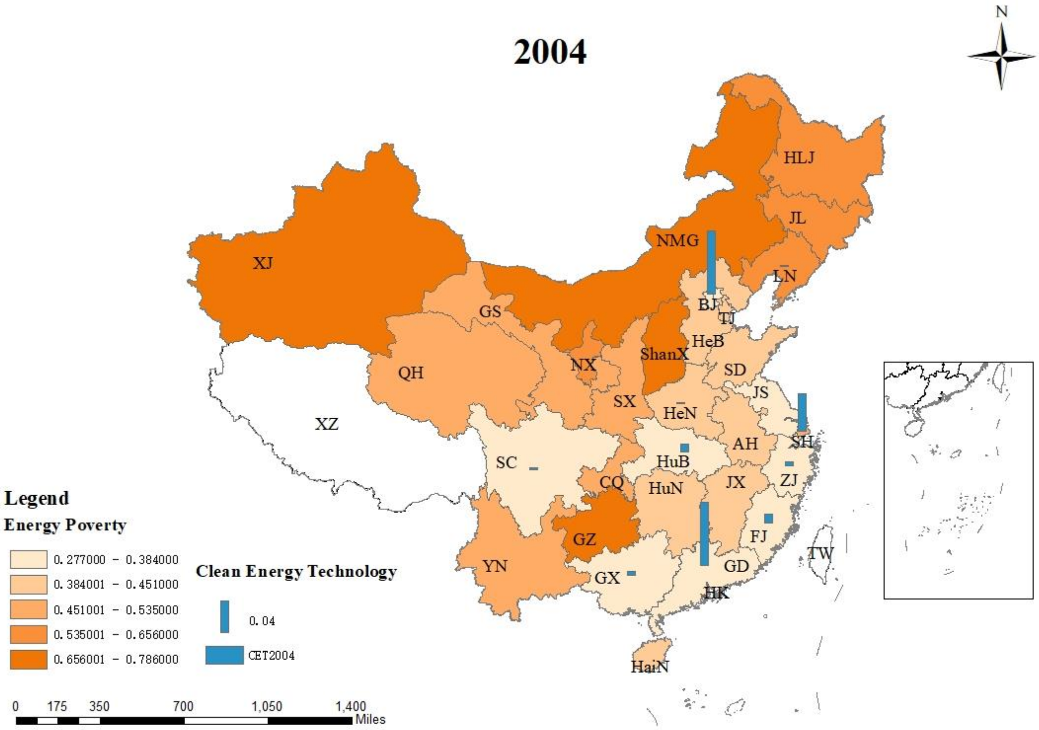

Fig.1. Provincial distribution of energy poverty and diffusion of clean energy technology in 2004.

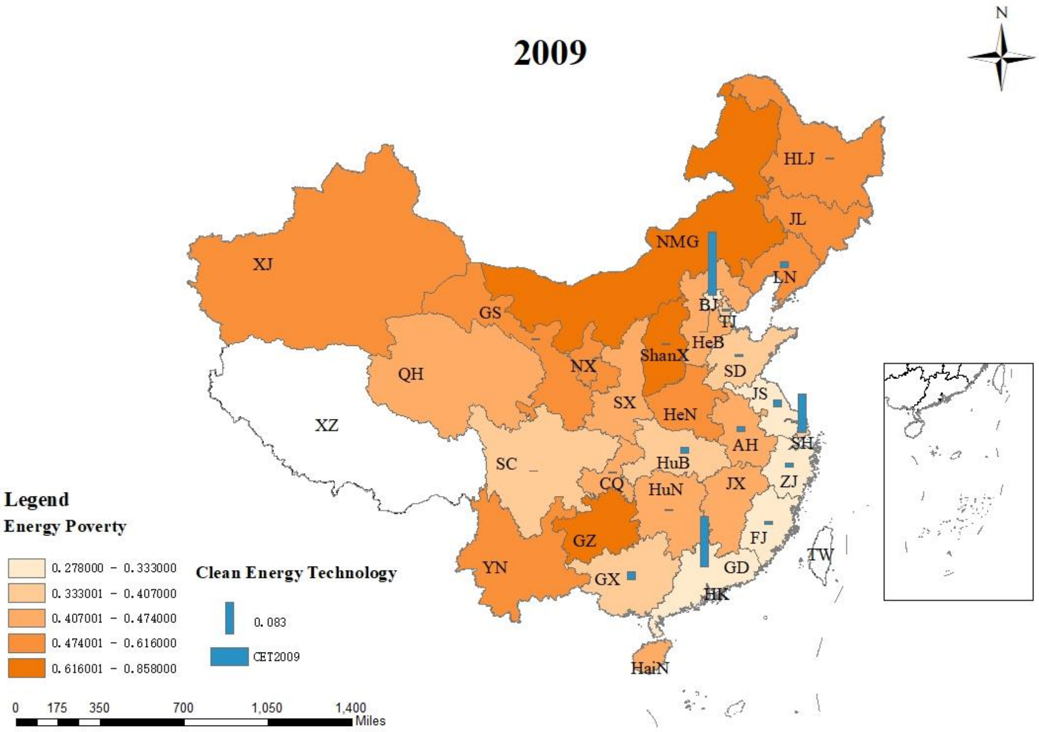

Fig.2. Provincial distribution of energy poverty and diffusion of clean energy technology in 2009.

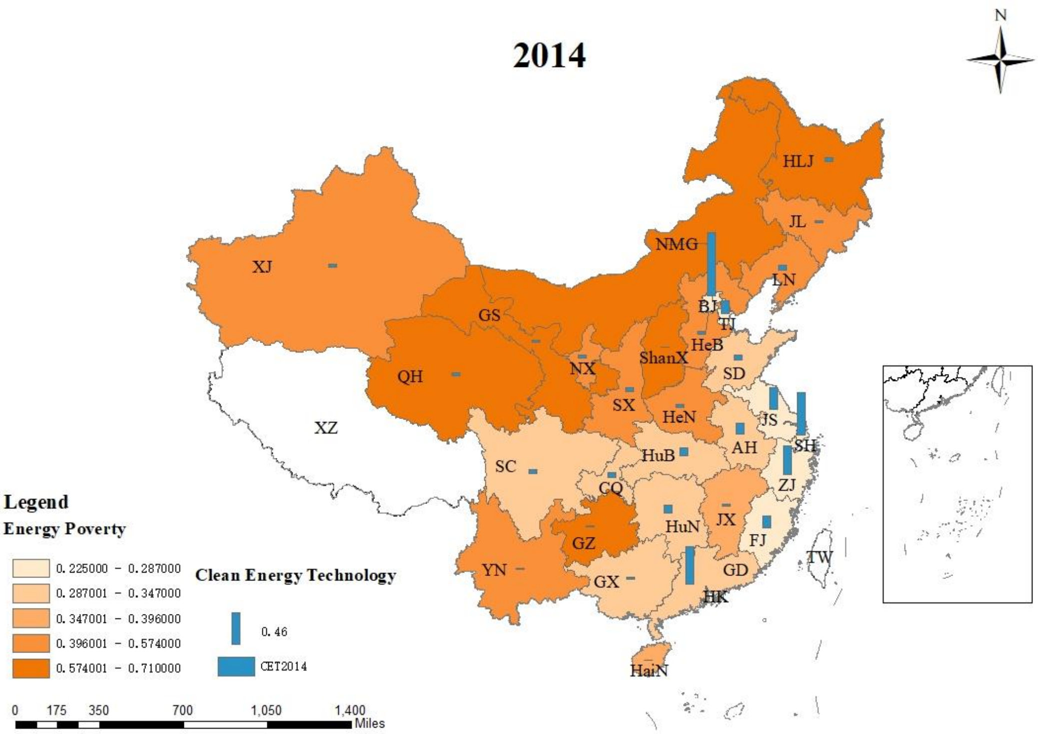

Fig.3. Provincial distribution of energy poverty and diffusion of clean energy technology in 2014.

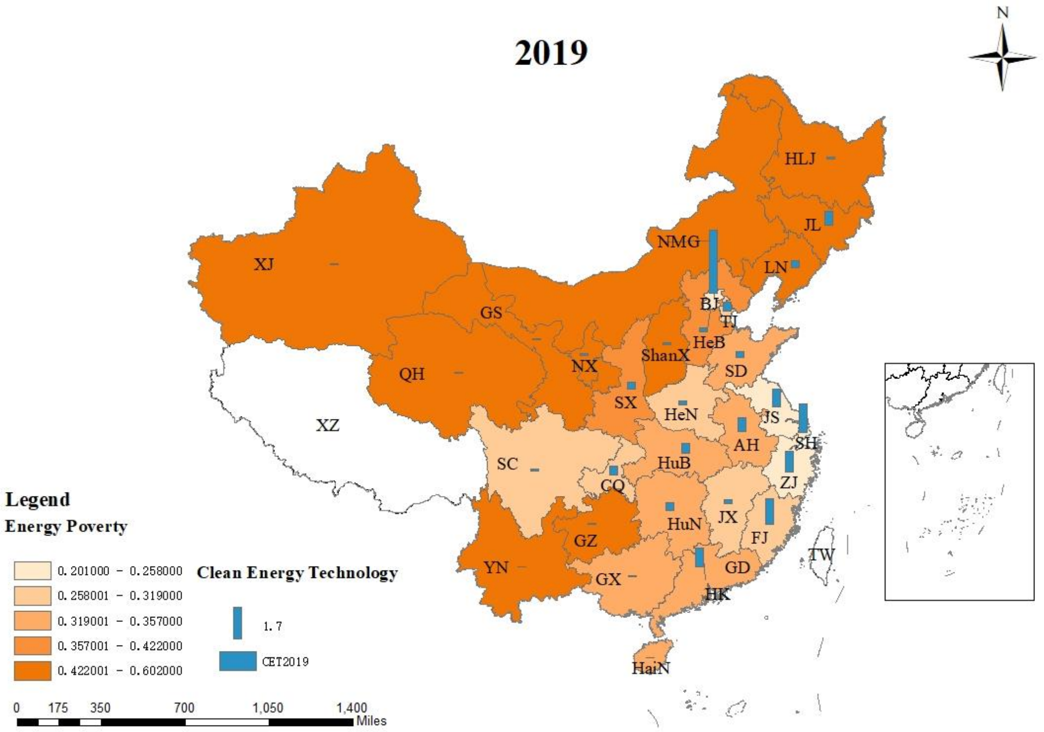

Fig.4. Provincial distribution of energy poverty and diffusion of clean energy technology in 2019.

4.2.2 Independent variable

Refer to the patent classification methods of Dechezleprêtre (2014) and Aghion et al. (2016), use the incoPat Global Patent Database to query and count the number of patent citations of clean energy technologies as shown in Table 1, and use the number of authorized patent citations per 10,000 people as a measure of technology diffusion. According to Fig.1, Fig.2, Fig.3 and Fig.4, we can see that the amount of technology diffusion in each province increases year by year, showing a pattern of more east and less west. At the same time, we matched the 206618 citation information of 46261 clean energy patents with 30 provinces, and used the visualization software Gephi to map the spatial correlation network of clean energy technology diffusion in 2004 and 2019 (see Fig.5 and Fig.6). We can find that China 's inter-provincial clean energy technology diffusion network has changed from a loosely linked network to a closely linked network, and the degree of connection between provinces ' clean energy technology diffusion has been increasing.

Table 1. Patent Classification of Clean Energy

patent classification	Cooperative Patent Classification
Clean energy patents	B60K1; B60L3; B60L7; B60L11； B60L15； B60R16；B60S5；B60W10；B60W20；H01M；H01J61；H05B33；F21K9；E02B9/08；F03D；F03G4；F03G6；F03G7/05；F24J2； F24J3/08； F26B3/28

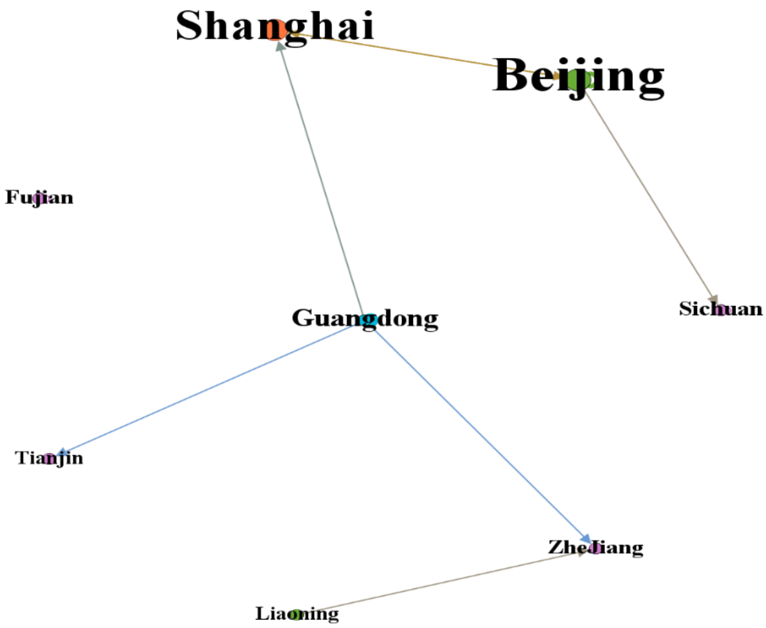

Fig.5. Diffusion of clean energy technology in 2004

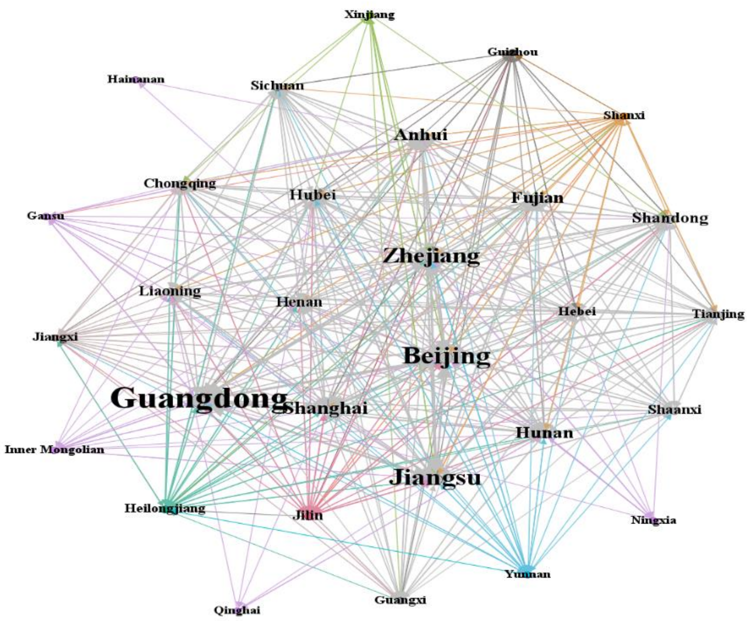

Fig.6. Diffusion of clean energy technology in 2019

4.2.3 Control variable

In order to accurately identify the causal relationship between diffusion of clean energy technology and energy poverty, we followed the research of Dong et al. (2022a) and Hong (2022) and selected appropriate control variables, including economic growth (PGDP), industrial structure (ISU), foreign investment level (OPEN), urbanization development (URB), urban road area per capita (ROAD) and education level (EDU). The specific descriptive statistics are shown in Table 2.

4.2.4 Mechanism variables and threshold variables

This paper selects energy efficiency (EI) and employment (JOB) as intermediary variables, human capital (HUMAN) as threshold variables. Referring to Duro et al. (2010) and Dong et al. (2022a), the reciprocal of energy intensity is used to evaluate energy efficiency, which is the ratio of GDP to total energy consumption in a province. Employment is measured by the number of employees in each province. Human capital is measured by the number of college students. The above data are from China Statistical Yearbook and China Energy Statistical Yearbook.

Table 2. Descriptive statistics of variables

variable	Meaning of variable	N	mean	sd	min	max
EP	Energy poverty composite index	480	-0.818	0.302	-1.604	-0.153
CET	Diffusion of clean energy technology	480	0.239	0.566	0	5.347
lnPGDP	Per capita gross domestic product	480	1.184	0.699	-0.864	2.799
lnISU	The ratio of tertiary industry to secondary industry output value	480	-0.0530	0.392	-0.704	1.643
lnOPEN	The ratio of foreign direct investment to GDP	480	-3.198	1.837	-9.142	0.162
lnURB	Ratio of urban population to total population	480	-0.654	0.263	-1.478	-0.0640
lnEDU	Ratio of average years of education to total population	480	2.164	0.113	1.853	2.548
lnROAD	Urban road area per capita	480	2.556	0.368	1.396	3.266
lnEI	Ratio of GDP to total energy consumption	480	0.119	0.561	-1.464	1.570
lnJOB	Quantity of employment	480	7.574	0.783	5.838	8.653
lnHUMAN	Number of college students per 10,000 people	480	5.098	0.377	3.830	5.876

5 Results and Discussion

5.1 Basic regression analysis

This paper aims to explore the impact of clean energy technology diffusion on energy poverty. We use a two-way fixed effects model to perform basic regression with the diffusion of clean energy technology and energy poverty as independent variable and dependent variables respectively. The Model (1) - (2) of Table3 shows the results without control variables and with control variables respectively. The estimation results of Model (2) show that the coefficient of the diffusion of clean energy technology is significantly negative at the level of 5 %, indicating that the diffusion of clean energy technology can significantly inhibit the occurrence of energy poverty, which verifies Hypothesis 1. Consistent with the research results that digital technology adoption, renewable energy technology innovation and clean energy development have a significant inhibitory effect on energy poverty (Hong, 2022; P. Wang et al., 2022; W. Wang et al., 2022), the diffusion of clean energy technology is an important means to alleviate energy poverty. On the one hand, the diffusion of clean energy technology can inhibit the occurrence of energy poverty by reducing the production cost of clean energy, increasing the market supply of clean energy, and reducing the use of fossil energy by residents. On the other hand, the development of clean energy technology has improved energy efficiency, reduced household energy demand, reduced energy consumption expenditure, and achieved energy poverty reduction.

In terms of the energy poverty reduction effect of control variables, foreign investment level and industrial structure have a significant role in alleviating energy poverty. Foreign investment level and industrial structure upgrading can effectively alleviate energy poverty by rationally allocating resources and improving energy efficiency. In addition, urbanization development has a significant inhibitory effect on energy poverty reduction. The possible reason is that the rapid development of urbanization in China has led to a significant increase in fossil energy demand and a significant increase in carbon emissions, which has hindered the process of energy poverty reduction (Dong et al., 2022b).

Table 3. Basic regression results

VARIABLES	(1)	(2)
CET	-0.101***	-0.089***
	(-5.79)	(-4.60)
lnPGDP		-0.045
		(-0.82)
lnISU		-0.109***
		(-2.68)
lnOPEN		-0.061***
		(-7.95)
lnURB		0.177*
		(1.72)
lnEDU		-0.238
		(-1.04)
lnROAD		0.002
		(0.05)
Control_pro	Yes	Yes
Control_year	Yes	Yes
Constant	-1.048***	-0.350
	(-29.55)	(-0.65)
Observations	480	480
R-squared	0.901	0.915

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

5.2 Robustness test

In order to ensure that the regression results of this paper are robust enough, we conducted a robustness test.

First, we increase the control variables. Existing research has shown that technological progress can alleviate energy poverty (Dong et al., 2022a). Therefore, this paper adds technological progress as a control variable and uses patent authorization to measure technological progress. The results of Model (1) of Table 4 show that the estimated results of the core explanatory variables do not change in the direction of influence compared with the benchmark regression, and only change at the significance level, which verifies the robustness of the regression results. In order to test the possible multicollinearity between variables, we conducted a variance inflation factor (VIF) test, and the regression results are shown in Table5. The VIF of each variable is less than 10, indicating that there is no serious multicollinearity between the explanatory variables, further indicating that the regression results are reliable.

Second, we eliminate the influence of municipalities. Different regions of China have different levels of technological development and different energy endowments, which may affect the mitigation effect of clean energy technology diffusion on energy poverty. Therefore, we exclude the data of Beijing, Tianjin, Shanghai and Chongqing from the total sample and then return. The regression results of Model (2) in Table4 still support Hypothesis 1.

Third, we exclude the impact of other exogenous policies. Since China has issued the " Energy Technology Revolution and Innovation Action Plan " and the " 13th Five-Year Plan for Energy Technology Innovation " in 2016, it aims to promote the energy technology revolution and give full play to the leading and supporting role of energy technology innovation in building a clean, low-carbon, safe and efficient modern energy system. The implementation of these policies may interfere with the energy poverty alleviation effect of the diffusion of clean energy technologies. In order to exclude the impact of these two policies, this paper removes the sample data from 2016-2019 and returns again. The results of Model (3) show that the coefficient of clean energy technology diffusion has increased and is still significantly negative, indicating that clean energy technology diffusion can still alleviate energy poverty, which verifies the robustness of the conclusions of this paper.

Table 4. Robustness test results

VARIABLES	(1)	(2)	(3)
CET	-0.087***	-0.529***	-0.146**
	（-4.47）	（-3.26）	(-2.34)
Control variables	Yes	Yes	Yes
Control_pro	Yes	Yes	Yes
Control_year	Yes	Yes	Yes
Constant	-0.164	0.808	-0.348
	（-0.30）	（1.62）	(-0.59)
Observations	480	416	360
R-squared	0.916	0.945	0.923

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

Table 5. The results of VIF test

VARIABLES	VIF	1/VIF
lnGDP	9.39	0.106
lnURB	6.14	0.163
lnTEC	3.17	0.315
lnEDU	2.68	0.373
lnOPEN	2.16	0.463
lnROAD	2.09	0.477
CET	2.04	0.489
lnISU	1.59	0.627
Mean VIF	3.66	

5.3 Endogeneity analysis

Considering that there may be missing variables and sample selection problems between clean energy technology diffusion and energy poverty, endogenous bias will occur in the model. In order to ensure the integrity of the research and the robustness of the conclusion, this paper uses the double difference method to deal with the endogenous problem. The difference-in-differences method is an important method to evaluate the effect of policy implementation. By dividing the sample group into the experimental group affected by the policy and the control group not affected by the policy, the difference between the two groups of samples before and after the policy impact is estimated, so as to identify the net effect of policy implementation. In October 2011, the National Development and Reform Commission issued the " Notice on the Pilot Work of Carbon Emissions Trading, " which aims to promote the continuous reduction of carbon emissions by carbon-emitting enterprises through carbon emissions trading, so as to promote enterprises to gradually reduce greenhouse gas emissions through technological progress. The implementation of the carbon emission trading rights policy has prompted enterprises to reduce the use of traditional fossil energy in production and operation, and tend to choose cleaner and low-carbon energy. Therefore, carbon emission reduction can be achieved by optimizing the energy consumption structure. At the same time, emission control enterprises are encouraged to further promote energy-saving technological innovation and the diffusion of clean energy technologies by increasing research and development investment, so as to improve energy utilization efficiency and achieve emission reduction effects. Therefore, this policy can be regarded as a relatively exogenous sudden impact to promote the diffusion of clean energy technology in the region. We construct the difference-in-difference model, as shown in Eq (5.1):

$$EP_{it} = \beta Treatment_i \times post_t + \delta control_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \qquad (5.1)$$

The independent variable $Treatment_i \times post_t$ is a policy dummy variable. If approved carbon emissions trading pilot[5], $Treatment_i$=1, otherwise 0. According to the start time of carbon emissions trading pilot in each province[6], set the pilot start time dummy variable Post. If in 2014 and later, Post = 1, otherwise 0. The coefficient β shows the impact of carbon emissions trading on energy poverty. If β is significantly negative, it shows that carbon emissions trading has a positive impact on energy poverty. $control_{it}$ is the set of control variables. α_i and γ_t are urban fixed effect and time fixed effect respectively. ε_{it} is a random perturbation term.

The premise of using the difference-in-differences method is that the experimental group and the control group meet the parallel trend assumption, that is, the trend of energy poverty is the same before the implementation of the carbon emission trading policy Fig.7 reports the results of the parallel trend test. The regression coefficients are not significant in the year before the policy implementation year, which satisfies the parallel trend hypothesis. The empirical results of Table6 show that the regression coefficient of $Treatment \times post$ is -0.050 and passes the 5% significance test, indicating that after dealing with the endogenous problems of the sample, the results are still consistent with the basic regression results of this paper.

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[5]On October 29,2011, the National Development and Reform Commission approved Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, Shenzhen to carry out pilot carbon emissions trading. Because Shenzhen is affiliated to Guangdong Province, the treatment group of this paper is Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei and other 6 provinces and cities, and the other 24 provinces constitute the control group of this paper.

[6]In addition to Shenzhen, which took the lead in launching the pilot of carbon emissions trading in June 2013, the other six pilot provinces only officially launched the pilot of carbon emissions trading in November, December 2013 and 2014. Therefore, 2014 was selected as the start year of the pilot of carbon emissions trading.

Table 6. DID results

VARIABLES	EP
Treatment×post	-0.050**
	(-2.10)
Control variables	Yes
Control_pro	Yes
Control_year	Yes
Constant	23.638*
	(1.77)
Observations	480
R-squared	0.912

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

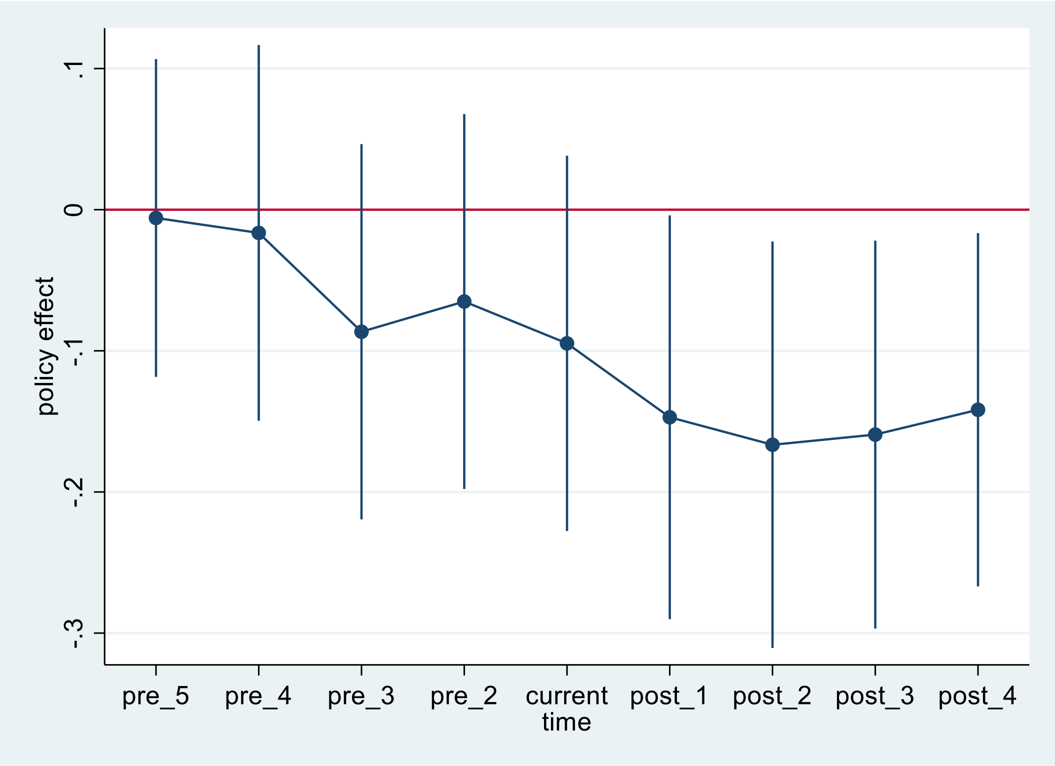

Fig.7. Statistics for parallel trend analysis

5.4 Mechanism test

In order to further explore the internal influence mechanism between the diffusion of clean energy technology and energy poverty, this paper uses the step-based regression method to test whether the diffusion of clean energy technology can alleviate energy poverty by improving energy efficiency and employment. The results are shown in Table7. Models (1) - (3) and (4) - (6) are the results of the mediating effect test with energy efficiency and employment as mediating variables. In Table7, Model (2) and Model (5) show that the coefficients of clean energy technology diffusion are 0.115 and 0.033, respectively, and are significant at the 1 % level, indicating that clean energy technology diffusion has a positive effect on energy efficiency and employment. The results of Model (3) and Model (6) show that the regression coefficients of clean energy technology diffusion to energy poverty are -0.072 and -0.081, respectively, and are significant at the 1 % level. The coefficients of energy efficiency and employment are -0.146 and -0.256, respectively, which are significant at the 1 % level. It shows that clean energy technology diffusion can alleviate energy poverty by improving energy efficiency and employment, and this conclusion is robust and significant, which verifies Hypothesis 1a and Hypothesis 1b. In other words, on the one hand, the diffusion of clean energy technology can improve energy efficiency, reduce energy consumption and energy consumption expenditure, thus alleviating energy poverty; On the other hand, the diffusion of clean energy technology can increase employment, increase residents ' disposable income, change the energy consumption structure, and thus inhibit the occurrence of energy poverty.

Table 7. Mechanism analysis results

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	EP	EI	EP	EP	JOB	EP
CET	-0.089***	0.115***	-0.072***	-0.089***	0.033**	-0.081***
	(-4.60)	(6.43)	(-3.59)	(-4.60)	(1.97)	(-4.27)
EI			-0.146***			
			(-2.81)			
JOB						-0.256***
						(-4.75)
Controlvariables	Yes	Yes	Yes	Yes	Yes	Yes
Control_pro	Yes	Yes	Yes	Yes	Yes	Yes
Control_year	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-0.350	-0.701	-0.453	-0.350	-2.120***	-0.938*
	(-0.65)	(-1.42)	(-0.84)	(-0.65)	(-4.50)	(-1.75)
Observations	480	480	480	480	480	480
R-squared	0.915	0.979	0.917	0.915	0.990	0.920

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

5.5 Asymmetric analysis

In order to further explore whether there are differences in the impact of clean energy technology diffusion on energy poverty at different levels of energy poverty, we refer to the research of Ren et al. (2022), and set five quantile indexes of 10th, 25th, 50th and 90th to evaluate the different conditional distributions of clean energy technology diffusion on energy poverty. The regression results are shown in Table 8. We find that the energy poverty alleviation effect of clean energy technology diffusion is only significant at the 10th, 25th and 50th quantiles, that is, the diffusion of clean energy technology will only have an impact on low-energy poverty areas. The possible reason is that the low-energy poverty provinces are mainly concentrated in the eastern region with high economic development level. On the one hand, the energy facilities in the eastern region are perfect, the cost of clean energy consumption is low, and the consumption capacity of residents for energy-saving commodities such as solar energy and natural gas is effectively enhanced. On the other hand, the level of human capital in the eastern region is high, and the innovation ability of clean energy technology is stronger (Dong et al., 2022b), which effectively improves the efficiency of energy utilization and accelerates the process of energy poverty reduction.

Table8. Quantile regression result

VARIABLES	10th	25th	50th	75th	90th
CET	-0.110***	-0.088***	-0.089**	-0.055	0.004
	(-4.56)	(-3.75)	(-2.51)	(-1.25)	(0.07)
Control variables	Yes	Yes	Yes	Yes	Yes
Control_pro	Yes	Yes	Yes	Yes	Yes
Control_year	Yes	Yes	Yes	Yes	Yes
Constant	1.47	0.785	0.353	-0.353	-0.997
	(2.07)	(1.13)	(0.43)	(-0.45)	(-1.00)
Observations	480	480	480	480	480
R-squared	0.784	0.756	0.741	0.728	0.732

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

5.6 Heterogeneity analysis

Considering the differences between the sources of diffusion and adoption of clean energy technology, regional resource endowments, and the level of economic development, the diffusion of clean energy technologies may have significant heterogeneity for energy poverty reduction. Therefore, we analyze the heterogeneity from three perspectives: diffusion and adoption sources, geographical regions and residents ' income levels.

Firstly, this paper divides the sources of technology diffusion and adoption into five regions: China, the United States, Europe, Japan and South Korea, and conducts heterogeneity analysis. The results are shown in Table 9. We found that clean energy technologies in these five countries can significantly reduce China 's energy poverty, but it is clear that foreign clean energy technologies have a better effect on energy poverty reduction, especially from the United States, South Korea and Europe. The possible reason is that with the development of international trade, foreign direct investment and patent licensing, compared with local research and development, developing countries ' absorption of international advanced technology diffusion is a low-cost way of technological change. This is similar to the research results of Sun et al. (2021). Compared with domestic energy technology innovation, foreign energy technology innovation plays a greater role in improving domestic energy efficiency. For example, the main driving force for energy efficiency improvement in the Netherlands is the technological development of the United States and Germany.

Table 9. Heterogeneity results of patent citation sources

VARIABLES	(1)	(2)	(3)	(4)	(5)
CHN	-0.121***				
	(-4.54)				
USA		-0.508***			
		(-4.05)			
EU			-3.669***		
			(-4.31)		
JPN				-1.331***	
				(-4.18)	
KR					-4.465***
					(-4.10)
Controlvariables	Yes	Yes	Yes	Yes	Yes
Control_pro	Yes	Yes	Yes	Yes	Yes
Control_year	Yes	Yes	Yes	Yes	Yes
Constant	-0.357	-0.241	-0.279	-0.229	-0.276
	(-0.66)	(-0.45)	(-0.52)	(-0.43)	(-0.51)
Observations	480	480	480	480	480
R-squared	0.915	0.914	0.915	0.915	0.915

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

Secondly, according to the geographical location of the province, the sample is divided into eastern, central and western regions, and group regression is performed as shown in Table 8. The coefficient of clean energy technology diffusion is only significantly negative in the eastern region, indicating that the diffusion of clean energy technology in the eastern region can alleviate energy poverty, but this energy poverty reduction effect has not been reflected in the central and western regions. It shows that the higher level of economic development, richer human capital and more complete energy infrastructure in the eastern region are conducive to amplifying the effect of clean energy technology diffusion on energy poverty reduction.

Finally, we use disposable income as the basis for grouping, and divide the samples into high-income groups and low-income groups for regression. Based on the results of Model (4) - (5) of Table 10, we find that the diffusion of clean energy technologies only helps residents in high-income provinces to alleviate energy poverty, and the impact on residents in low-income provinces is not significant. This may be due to the higher price of modern clean fuels and the preference of low-income residents for more accessible solid fuels (Jain, 2010). In areas with higher income levels, residents are not only more able to pay for clean and green energy, but also have better energy infrastructure (Castaño-Rosa and Okushima, 2021). Therefore, the diffusion of clean energy technologies is more helpful for high-income residents to spread energy poverty. This conclusion is consistent with the research results of Barnes et al. (2011). They believe that when the household income is in a low-income state, its energy consumption will not increase with the increase of income. Only by crossing the low-income threshold, the level of energy consumption will increase with the increase of income level.

Table10. Regional and income heterogeneity analysis results

	(1)	(2)	(3)	(4)	(5)
VARIABLES	Eastern	Central	Western	High income	Low income
CET	-0.082***	0.068	-0.271	-0.0672**	-0.266
	（-3.28）	（0.72）	（-1.56）	(-2.48)	(-0.51)
Controlvariables	Yes	Yes	Yes	Yes	Yes
Control_pro	Yes	Yes	Yes	Yes	Yes
Control_year	Yes	Yes	Yes	Yes	Yes
Constant	-0.758	1.529	-0.360	0.447	-0.077
	（-0.69）	（1.76）	（-0.50）	（0.42）	(-0.13)
Observations	176	128	176	208	272
R-squared	0.894	0.934	0.902	0.941	0.926

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

The eastern region includes China's 11 provinces of Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Hainan and Guangdong. The central region contains 8 provinces of Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan. The western region consists of 11 provinces of Inner Mongolian, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Yunnan, Gansu, Qinghai, Ningxia.

5.7 Panel threshold model analysis

As an effective carrier of knowledge flow, human capital not only determines a country 's ability to attract technology, but also affects its technology catch-up and technology diffusion speed. Therefore, we select human capital as the threshold variable.

First, we determine whether the model has threshold utility, and test the single threshold, double threshold and triple threshold in turn. The test results are shown in Table 11. The P-value of the double threshold of clean energy technology diffusion is 0.123, the result is not significant, and the single threshold is significant at the level of 1 %, indicating that there is only a single threshold. The threshold value of the single threshold is 5.187, that is, the number of college students per 10,000 people in each province is 179.

Table11. Threshold effect test results

Threshold	F	P	Crit10	Crit5	Crit1
Single threshold	37.99	0.007	25.415	30.083	37.393
Double threshold	11.83	0.123	14.072	17.144	24.032
Triple threshold	13.61	0.360	25.310	32.082	43.078

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

Crit10, Crit5 and Crit1 indicate the critical value levels in 10%, 5% and 1%, respectively.

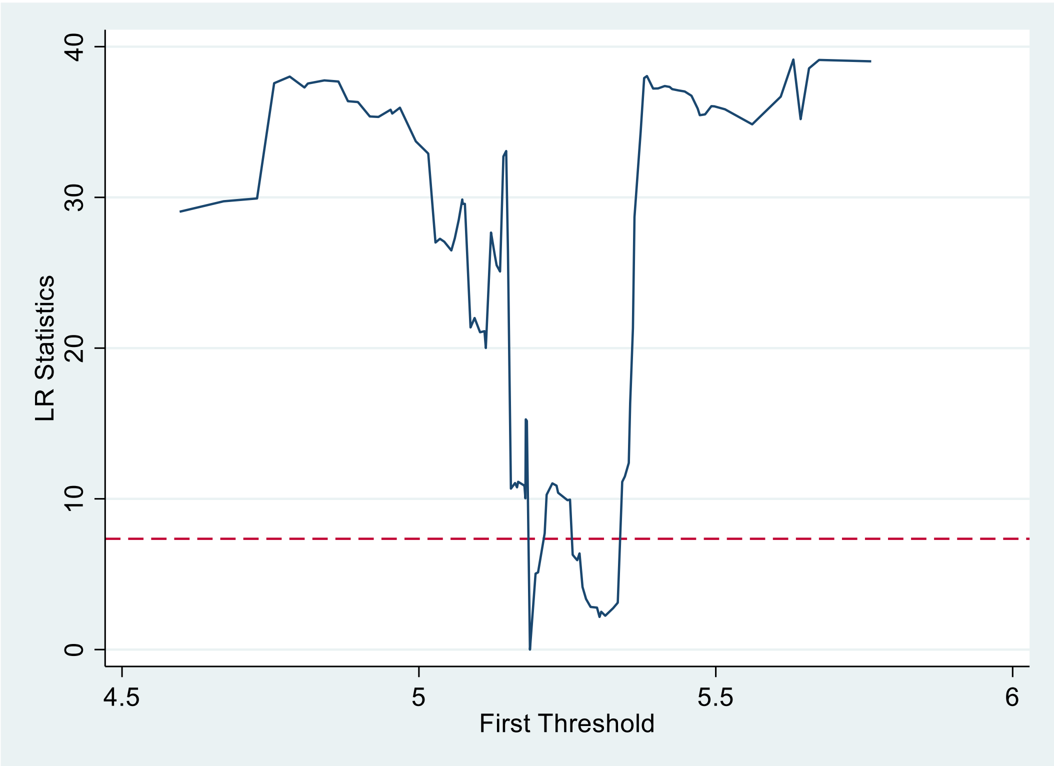

Fig. 8. Confidence interval construction for a Single-threshold model.

Second, according to the principle of threshold model, the threshold estimation value is the γ value corresponding to the likelihood ratio statistic LR approaching 0, Fig.6 is the likelihood ratio function diagram of the single threshold estimation value 5.187 under 95 % confidence interval. Among them, the lowest point of LR statistic is the corresponding true threshold value, and the dotted line indicates that the critical value is

7.35. Since the critical value is 7.35, which is significantly larger than the threshold value, the authenticity and effectiveness of the estimation results are proved.

Finally, after establishing the threshold value, we conduct panel threshold regression. The threshold regression results show that when human capital is lower than the threshold value of 5.187, the influence coefficient of clean energy technology diffusion on energy poverty is 0.242, which is significant at the level of 1 %. When the human capital is greater than the threshold value of 5.187, the influence coefficient changes from positive to negative, with a value of -0.071 and significant at the level of 10 %. The results show that there are significant differences in the impact of knowledge diffusion of clean energy technology on energy poverty under different human capital levels. Only when human capital crosses a single threshold can the diffusion of clean energy technology play a role in energy poverty reduction. This conclusion is consistent with the results of Akhvlediani and Cieślik (2020). It can be seen that human capital plays an important role in the process of clean energy technology diffusion to alleviate energy poverty. It shows that the cultivation and introduction of high-tech talents in the future energy sector and the promotion of human capital accumulation are crucial for the diffusion of clean energy technology to exert energy poverty reduction effect.

Table12. Panel threshold regression results

Variables	Panel threshold model	
	Coef.	t-statistic
CET (lnHUMAN≤5.187)	0.242***	4.51
CET (lnHUMAN> 5.187)	-0.071***	-3.82
Constant	0.728	1.51
N	480	480
Control	Yes	
R^2	0.297	

6 Conclusions and policy implications

6.1 Conclusion

Focusing on whether the diffusion of clean energy technology can alleviate energy poverty, we use the multidimensional energy poverty index method to measure the energy poverty index of 30 provinces in China from 2004 to 2019, and uses patent citation information to systematically analyze the impact and mechanism of clean energy technology diffusion on energy poverty for the first time. The main results are as follows:

First, clean energy technology diffusion is an effective way to achieve energy poverty reduction. Consistent with previous studies that digital technology adoption, renewable energy technology innovation and clean energy development play an important role in energy poverty reduction (Hong, 2022; P. Wang et al., 2022; W. Wang et al., 2022), the diffusion of clean energy technology can effectively alleviate energy poverty. On the one hand, the adoption of clean energy technologies by enterprises can directly affect carbon emissions and have an alternative effect on highly polluting fossil energy. on the other hand, the use of clean technology by households can significantly improve energy efficiency, generate energy-saving effects, and improve residents ' welfare.

Second, energy efficiency and employment can play an important intermediary role between energy technology diffusion and energy poverty by exerting energy saving effect and income growth effect respectively. Mechanism analysis shows that, on the one hand, the diffusion of clean energy technology can improve energy efficiency, produce energy-saving effect, reduce the basic energy demand of residents, and thus alleviate energy poverty. On the other hand, the diffusion of clean energy technology can promote employment, increase the disposable income of residents, enhance the purchasing power of clean energy, improve the energy consumption structure, and thus inhibit the occurrence of energy poverty. The threshold model shows that only when the number of college students per 10,000 people in each province is higher than 179, the diffusion of clean energy technology can achieve the effect of curbing energy poverty. This is related to the high entry threshold of clean energy technology, and the development of clean energy industry depends on the development of human capital to a certain extent. With the improvement of human capital level, technology absorptive capacity can amplify the inhibitory effect of clean energy technology diffusion on energy poverty.

Finally, the inhibitory effect of clean energy technology diffusion on energy poverty varies greatly due to technical and regional differences. The analysis of the mitigation effect of clean energy technology diffusion from different countries on China 's energy poverty shows that foreign clean energy technologies have stronger energy poverty reduction capabilities. The reason is that countries such as the United States, Japan and the European Union hold the key technologies of clean energy in the world, while China 's clean energy technology is in the stage of introduction, digestion and joint design, and lacks independent intellectual property rights, so it has no advantage in alleviating energy poverty. At the same time, the energy poverty reduction effect of clean energy technology diffusion is more significant in the eastern and high-income areas, indicating that higher levels of economic development may amplify the effect of clean energy technology diffusion on energy poverty reduction. Related to this, quantile regression shows that this poverty reduction effect is only significant in low-energy poverty areas. These areas are also concentrated in the eastern coastal areas. It shows that there may be a Matthew effect of ' the richer the rich, the poorer the poor ' (Rogers, 2010).

6.2 Policy implications

Based on the above conclusions, we propose the following policy implications.

First of all, local governments should actively play the role of clean energy technologies in energy poverty reduction. Starting from the current situation of energy poverty, we should explore a differentiated development model of clean energy technology according to local conditions. In the eastern region with low-energy poverty and some economically developed provinces, give full play to their economic advantages, technological advantages, talent advantages and geographical location advantages, and further amplify the energy poverty reduction effect of clean energy technology diffusion. In the central and western regions with high-energy poverty, we should make full use of their energy endowment advantages and policy support advantages, accelerate the construction of clean energy infrastructure, and improve the energy efficiency of residents.

Second, the government can try to use household clean energy subsidy policies to play the energy poverty reduction role of clean energy technologies. For example, encourage households to use clean and efficient energy such as biogas, solar energy and natural gas, and supporting household rooftop photovoltaic installation. At the same time, subsidy policies should be coordinated with employment policies, such as attracting rural youth to participate in rooftop photovoltaic services, and amplifying the effects of clean energy technologies by increasing the income of poor households.

Third, since the use of clean energy technologies in developed countries such as Europe and the United States at this stage is an efficient means to alleviate energy poverty in China, the government and enterprises should maintain a more open attitude, actively introduce foreign investment, and strengthen cooperation with foreign-funded enterprises to promote the diffusion of foreign advanced clean energy technologies.

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