The role of green finance in eradicating energy poverty: ways to realize green economic recovery in the post-COVID-19 era

Jun Zhao[1,2] · Jianda Wang[1,2] · Kangyin Dong[1,2] 📷

Abstract

Realizing green economic recovery and eradicating energy poverty have become China's strategic priorities in the post-COVID-19 era. In the context of the active advocacy of green finance, to empirically investigate whether green finance can help eradicate energy poverty, this study utilizes provincial sample data to explore the energy poverty eradication effect of green finance. Our study also examines the regional heterogeneity and mediating effect. The main findings are as follows: (1) Green finance is a powerful weapon to alleviate China's energy poverty and accelerate green economic recovery, indicating that the green evolution of financial institutions is effective means to facilitate green economic recovery in the post-COVID-19 era; (2) green finance only eradicates energy poverty in low energy poverty regions and the eastern areas, and green finance can alleviate energy poverty in both high and low green finance areas; and (3) improved green finance not only directly eradicates China's energy poverty, but also alleviates current energy poverty by accelerating technical innovation and optimizing the industrial structure. Following the above main findings, this study advances a series of policy implications in terms of facilitating the green transition of the financial industry and realizing green economic recovery.

✉ Kangyin Dong
dongkangyin@uibe.edu.cn

Jun Zhao
zhaojun4768@163.com

Jianda Wang
wangjd1993@163.com

1   School of International Trade and Economics, University of International Business and Economics, Beijing 100029, China

2   UIBE Belt & Road Energy Trade and Development Center, University of International Business and Economics, Beijing 100029, China

1 Introduction

In 2015, all members of the United Nations adopted the 2030 Sustainable Development Agenda which incorporates Sustainable Development Goals (SDGs) to ensure universal access to affordable, reliable, and modern energy services until 2030 (UN 2020). However, according to statistics from the International Energy Agency (IEA), approximately 670 million people worldwide cannot obtain sufficient electricity by 2030 under the current policies (IEA 2021). At the same time, the 26th United Nations Climate Change Conference (COP26) held in Douglas UK in November 2021, discussed in-depth global actions to reduce emissions (Dwivedi et al. 2022). Calls for a renewable energy transition are growing as commitments to net-zero emissions increase around the world to achieve the 1.5 °C target set by the Paris Agreement. Therefore, to meet the SDGs and emission-reduction initiatives as well as achieve the green economic recovery in the post-COVID-19 era across the globe, finding ways to establish clean renewable energy to produce electricity has become the focus of global future development (Dong et al. 2021a; Taghizadeh-Hesary et al. 2021). On this basis, according to the requirements of SDGs, the IEA (2021) defines energy poverty as a lack of clean fuels such as electricity and cooking facilities, and highly relying on traditional solid biomass and firewood.

As the world's largest energy consumer and most populous country, China has faced severe energy poverty in the past century. However, with the continuous emission-reduction efforts of the Chinese government, preliminary mitigation results have been achieved (Dong et al. 2020; Cheng et al. 2021; Ren et al. 2022). From 2000 to 2019, the ratio of people obtaining electricity in China rises from 98.6% to 100%, and the residents using clean cooking have also increased from 46.8% to 71.3% (IEA 2020; Zhao et al. 2021a). China's per capita electricity consumption has exceeded that of average upper-middle income countries. However, due to China's huge population, the large gap between rich and poor, and uneven regional development, the country still suffers from energy poverty (Lin and Wang 2020). According to data from China Family Panel Studies (CFPS), in 2014, 41% of households in rural China still depended on firewood for cooking fuel (CFPS 2022). As the COVID-19 continues to evolve, actions such as layoffs or quarantines have significantly reduced income levels, further exacerbating energy poverty. Accordingly, energy poverty is still the top priority in China's poverty alleviation efforts.

In view of the important influence of energy poverty in China, many scholars have explored different ways to reduce energy poverty, such as low-carbon energy transition (Dong et al. 2021a, b), energy security (Taghizadeh-Hesary

et al. 2022), off-farm work (Lin and Zhao 2021), renewable energy consumption (Zhao et al. 2022), and addressing income inequality (Igawa and Managi 2022). However, some scholars have pointed out that green finance has a tendency to reduce energy poverty, which is a reaction to insufficient renewable energy investment (Markham et al. 2014; Mohsin et al. 2021; Wang and Wang 2021; Yang et al. 2021). On the one hand, green finance is recognized as an effective tool to achieve green economic growth and structural transformation, and the use of green finance can actively facilitate green transition, especially in the post-COVID-19 era (Wang and Wang 2021). On the other hand, green finance also contributes to the development of clean energy technologies and investments, and enhances technical innovation intensity, thereby reducing energy poverty (Taghizadeh-Hesary and Yoshino 2020; Li et al. 2021). Under the United Nations Framework Convention on Climate Change, full implementation of the Paris Agreement which aims to achieve the 1.5 °C target will require 1.5 trillion dollars in green financing annually by 2030 (Azhgaliyeva and Liddle 2020). Therefore, it is imperative to examine whether developing green finance is an effective way to address energy poverty and facilitate green economic recovery in the post-COVID-19 era. Accordingly, in this paper, we will examine the following three questions in detail: (1) Does green finance have the potential to eradicate China's energy poverty and accelerate green economic recovery in the post-COVID-19 era? (2) Does green finance have heterogeneity impacts on energy poverty? (3) What is the mechanism by which green finance affects energy poverty? To solve the above issues, this study explores whether green finance has the potential to eradicate energy poverty by using balanced sample data in 30 provinces in China for the period 2004–2018. Furthermore, we examine the heterogeneity and mediating mechanisms in the green finance–energy poverty nexus.

Consequently, this paper contributes to the existing literature in the following three ways. First, we empirically discuss whether developing green finance has the potential in alleviating energy poverty and facilitating green recovery of the economy in the post-COVID-19 era; this exploration has implications for the Chinese government and even many governments in developing countries, and provides a valuable reference for them to formulate energy mitigation policies in the future. Second, this paper investigates the heterogeneity of green finance development on energy poverty, which has important benefits for China in narrowing the uneven urban–rural energy development level and the energy poverty gap. Third, we also examine the mechanism through which green finance alleviates energy poverty. This discussion provides a reference direction for the government to develop policies and measures related to fuel poverty by considering the roles of technical progress and industrial adjustment.

We present the remainder of this paper in the following sections. The next section provides the relevant literature on green finance and energy poverty, followed by the theoretical framework built in Sect. 3. Section 4 represents the methodology and data. Estimated findings of this study are illustrated in Sect. 5. Section 6 further explores the mediating role of technical progress and industrial adjustment in the green finance–energy poverty nexus. Section 7 concludes our study and develops a series of policy suggestions.

2 Literature review

2.1 Research on green finance

To the best of our knowledge, green finance refers to financial instruments that provide environmental benefits. Traditional financial markets focus on the profitability of investment projects, and ignore the impact on the environment. As a result, green finance drives the transition of massive investments from those that result in high pollution to those that promote resource conservation (Yang et al. 2021). Cowan (1999) points out that green finance is concerned with the practical issues related to paying for the level of environmental protection rather than how or why or what the society decides. In 2000, the American traditional dictionary summarized the definition of green finance. The dictionary states that as part of environmental economy, green finance should facilitate the evolution of environmental finance and environmental industry through various financial instruments, so as to realize the protection of the environment and biodiversity (Wang and Wang 2021).

Based on the above scholars' definition of green finance and the vigorous publicity and widespread popularization of green concepts in the global financial industry, a growing body of scholars has conducted in-depth explorations on green finance (Weber and ElAlfy 2019; Zhang et al. 2019b; Akomea-Frimpong et al. 2021). Since China became the world's largest energy consumer and greenhouse gas emitter, and also the largest green bond issuer between 2016 and 2019 (Azhgaliyeva and Liddle 2020), the evolution of its green finance has received increasing attention (Lv et al. 2021; Wang et al. 2021). For example, Yin and Xu (2022) explore the relationship between green finance and economic level in China using a coupling coordination degree model. Their results indicate that green finance is lagging behind economic growth. Wang and Wang (2021) use the grey correlation method to empirically test the relationship between green finance and the upgrading of China's industrial structure. Their results imply that green finance produces the greatest driving effect on tertiary industry, facilitating the rapid development of tertiary industry and promoting upgrading of the industrial structure. Yang et al. (2021) quantitatively explore the linkage between green finance, financial technology, and high-quality evolution. Their findings provide strong support for the effective role of green finance in promoting high-quality economic evolution. However, green finance requires funds not only to invest in projects such as green industries and environmentally friendly infrastructure, but also to consider potential environmental impacts (Khan et al. 2021; Wang et al. 2021; Yin and Xu 2022). Zhou et al. (2020) empirically check the role of green finance in the financial industry in the coordinated development of the economy and environment by using Chinese provincial data from 2010 to 2017, and point out that green finance can achieve a win–win situation for both environmental quality and economic development. Muganyi et al. (2021) apply the semi-parametric difference-in-difference method to find that the relevant policies of green finance generally reduce industrial gas emissions in China.

2.2 Research on the green finance–energy poverty nexus

Some scholars believe green financing will help alleviate energy poverty. This is because green finance can speed up the energy transition and economic development (Hafner et al. 2021; Ngo et al. 2021), make modern energy affordable in countries living at lower levels of development, and alleviate energy shortages. For example, Setyowati (2020) points out that the Indonesian government should mobilize the private sector to provide large-scale climate finance for renewable energy generation, which is critical for Indonesia to achieve its renewable energy goals and provide electricity to people living in energy poverty. After examining the relationship between factors such as energy poverty and economic development in seven South Asian countries, Amin et al. (2020) find that increasing the proportion of capital investment in renewable energy-related sectors is conducive to the rapid growth of economy and the mitigation of energy poverty. Azhgaliyeva and Liddle (2020) point out that investment in fossil fuel still dominates energy investment, which could threaten the expansion of green energy needed to deliver energy security and meet climate and clean air goals. Aassouli et al. (2018) also indicate that achieving the SDGs and sustainable energy inclusion in the sub-Saharan region requires them to focus on investment in green projects, so green finance is a good channel to address energy poverty. Moreover, energy access is critical for meeting a wide range of development challenges, including poverty reduction (Gujba et al. 2012; Ansu-Mensah and Kwakwa 2022). Therefore, many scholars have also explored the impact of green finance on energy access. Duppati et al. (2021) identify the size of the funds committed to energy access initiatives in the African region as critical in ensuring a positive relationship between green finance and electricity access. Okesola (2021) proposes bridging the energy supply gap and improving electricity supply by creating a federal green bank to promote investment in renewable energy.

2.3 Literature gaps

Although many scholars have systematically summarized green finance and its impact on the economy and environment, knowledge gaps still exist. First, a growing body of scholars has measured green finance from different perspectives; few scholars have assessed the current development situation of green finance, especially in China. Second, the potential effects of the evolution of green finance are explored from various aspects by many studies (see Sect. 2.1), relevant research on the green finance–energy poverty nexus is still in an exploratory stage, and related studies in China are still rare. Whether developing green finance in China can help facilitate green economic recovery in the post-COVID-19 era is also worth exploring. Third, the mechanism by which green finance affects energy poverty is still unclear, especially the typical ways of affecting technical progress and industrial adjustment. Filling the gaps of the above studies can help scholars and governments formulate green financial solutions to alleviate energy poverty more clearly.

3 Theoretical framework

In recent years, the connotation of green finance has been expanding, and a green financial service system with commercial banks as the core has been gradually formed (Taghizadeh-Hesary and Yoshino 2019). Green finance adopts financial instruments such as green stocks, green bonds, green insurance, and carbon finance to provide capital base for green and low-carbon economic transition. The construction of green financial system, the development of green financial products, and the introduction of relevant policies have laid favorable market conditions for the green development of different industries, especially the clean and renewable energy industry (Rasoulinezhad and Taghizadeh-Hesary 2022). Through the leverage of capital market, green finance can effectively redirect capital flow, restrain loans of polluting production projects, and actively guide the transfer of capital to green technology projects in the energy industry (Muganyi et al. 2021); more specifically, the government will introduce relevant policies to improve green investment bank, actively guide financial institutions to invest in the facility construction and technology research of renewable energy industries such as wind energy and solar energy, increase the total power supply, reduce the cost of clean energy, and gradually replace the use of traditional solid biomass and polluting fossil energy, thereby alleviating energy poverty.

In addition, the increasing introduction of green finance policies, on the one hand, will help support the implementation of green innovation systems (Molla et al. 2019; Zeng et al. 2022). Financial methods such as green credit and green bonds can effectively promote enterprises' investment in environmental protection equipment, strengthen the development of clean technology, and facilitate enterprises to become the backbone of green innovation. Furthermore, green finance is an effective market-oriented means for local governments to gather social forces to serve the environmental protection industry. The research and development (R&D) of environmental protection technology has the characteristics of large investment and long cycle (Huang et al. 2021). It is necessary to reduce the cost and risk of the development of enterprises through financing means, and maintain the enthusiasm and determination of enterprises and society to develop green technologies. On the other hand, the advocacy of green finance effectively reduces the capital accumulation of high-polluting industry (Zhang et al. 2021). Through the guiding role of capital, polluting and backward production capacity can be phased out in accordance with the principles of green, efficient, intensive, and safe, industrial optimization and upgrading can be accelerated. As Zhao et al. (2021a, b) and Wang et al. (2022) stress, the vigorous promotion of technical innovation and rapid upgrading of industrial structure can effectively facilitate the evolution of renewable energy industry, promote the optimization of energy system, adjust the energy supply and demand pattern, and thus alleviate energy poverty. To this end, we develop the following two hypotheses:

Hypothesis 1 Green finance is a powerful weapon to eradicate energy poverty.

Hypothesis 2 Green finance can help eradicate energy poverty through industrial structure upgrading and technological innovation.

4 Methodology and data

4.1 Model construction

Our paper aims to investigate whether green finance is a powerful weapon to eradicate energy poverty and promote green economic recovery in the post-COVID-19 era; that is, whether the increased evolution of green finance can eradicate China's energy poverty. In doing so, the empirical econometric model is constructed in the following equation:

$$
\begin{aligned}
\ln EPI_{it} =& \alpha_0 + \alpha_1 \ln GFI_{it} + \alpha_2 \ln Tec_{it} + \alpha_3 \ln Ind_{it} + \alpha_4 \ln Pgdp_{it} + \alpha_5 \ln Edu_{it} \\
& + \alpha_6 \ln FDI_{it} + \alpha_7 \ln Wag_{it} + \eta_i + v_t + \varepsilon_{it}
\end{aligned}
\tag{1}
$$

where the subscripts i and t refer to China's specific provinces and the sample period (i.e., 2004–2018), respectively. EPI represents the energy poverty composite index, GFI indicates the green finance index, Tec denotes technical process, Ind means industrial structure adjustment, $Pgdp$ stands for economic level, Edu represents education level, FDI refers to foreign investment level, and Wag indicates residents' wage level. α_0 is the intercept term, and $\alpha_k(k = 1, 2, ..., 7)$ are the coefficients that need to be estimated. η_i, v_t, and ε_{it} refer to the provincial effect, time effect, and error term, respectively. In this equation, we expect the coefficient of green finance (i.e., α_1) to be negative.

Considering the potential dynamic effect of the green transformation of financial institutions to eradicate energy poverty, we introduce the lag term of energy poverty into Eq. (1) for econometric regression; the specific equation is illustrated as follows:

$$
\begin{aligned}
\ln EPI_{it} =& \beta_0 + \beta_1 \ln EPI_{i,t-1} + \beta_2 \ln GFI_{it} + \beta_3 \ln Tec_{it} + \beta_4 \ln Ind_{it} + \beta_5 \ln Pgdp_{it} \\
& + \beta_6 \ln Edu_{it} + \beta_7 \ln FDI_{it} + \beta_8 \ln Wag_{it} + \eta_i + v_t + \varepsilon_{it}
\end{aligned}
\tag{2}
$$

where β_0 represents the intercept term, and $\beta_k(k = 1, 2, ..., 8)$ refer to the coefficients of the variables that need to be assessed.

Regarding the estimated method for the dynamic panel model, the generalized method of moments (GMM) technique, which performs the first difference on Eq. (2), is used to solve potential endogeneity within the econometric equation; Eq. (2) in the first-order difference is shown as follows:

$$
\Delta \ln EPI_{it} = \beta_1 \Delta \ln EPI_{i,t-1} + \beta_2 \Delta \ln GFI_{it} + \sum_{k=3}^{8} \beta_k \Delta \ln Z_{it} + \Delta \eta_i + \Delta v_t + \Delta \varepsilon_{it}
\tag{3}
$$

where Δ refers to the first-order difference form of the variables, and Z denotes a vector consisting of *Tec*, *Ind*, *Pgdp*, *Edu*, *FDI*, and *Wag*.

Two main types of GMM estimation method—differential GMM (Diff-GMM) and system GMM (Sys-GMM)—are applied in the econometric regression in our study. It is worth noting that the latter (i.e., Sys-GMM) incorporates Eqs. (2) and (3) into a unified framework for systematic analysis, which can more effectively address potential endogeneity issues and provide consistent estimates compared to the former (i.e., Diff-GMM) (Pan et al. 2021; Zhao et al. 2021b); therefore, this study employs the estimated results of the Sys-GMM strategy as the benchmark regression.

4.2 Variable measures and data sources

4.2.1 Explained variable

Energy poverty (*EPI*). In recent years, China has achieved remarkable results in energy poverty (Zhang et al. 2019a; Dong et al. 2021b); thus, to effectively evaluate the current situation of energy poverty in China, this study constructs a comprehensive index system of energy poverty by referring to the relevant studies of Wang et al. (2015) and Zhao et al. (2021a), which mainly include four aspects: energy access capability, energy cleanliness, energy infrastructure completeness, and energy efficiency & resident affordability; the specific measurement, code, and property of the indicators are presented in Table A1 in the Appendix. In this indicator system, significant differences exist in the dimensions of each indicator. Thus, we utilize the improved entropy method to gauge China's energy poverty. The specific calculation steps of this technique can refer to the work of Zhao et al. (2021a). We also calculate the sub-index of the four aspects, i.e., energy access capability index (*EP_1*), energy cleanliness index (*EP_2*), energy infrastructure completeness index (*EP_3*), and energy efficiency and resident affordability index (*EP_4*). The relevant data of the indicators are obtained from the China Statistical Yearbook (CSY 2021) and the China Energy Statistical Yearbook (CESY 2021).

After calculating the composite index and sub-indexes of energy poverty, we first draw the time trend chart of average energy poverty to describe the actuality of energy poverty eradication (see the line chart in Fig. 1). Clearly, China's energy poverty has been significantly reduced over the sample period. Furthermore, the spatial pattern of energy poverty in 2004, 2009, 2014, and 2018 is presented in Fig. 2 due to the space limitations of the article. We find that significant regional heterogeneity exists across different provinces. For example, energy poverty in the northern provinces is much worse than that in the eastern coastal provinces.

4.2.2 Explanatory variables

Green finance (*GFI*). As a product of green economy, energy finance can effectively facilitate the flow of capital to the field of environmental protection and green technological innovation, so as to prevent environmental degradation. Similar to energy

Table 1 Definitions and descriptive statistics of the selected variables

| Variable	Definitions	Mean	Std. Dev.	Minimum	Maximum
ln*EPI*	Energy poverty composite index calculated in Sect. 4.2.1	−0.8996057	0,369,924	−1.997315	−0.1197464
ln*GFI*	Green finance composite index calculated in Sect. 4.2.2	−1.347638	0.367188	−2.031035	−0.1971542
ln*Tec*	Technical process measured by the number of domestic patent applications authorized	9.178403	1.654187	4.248495	13.07754
ln*Ind*	Industrial structure adjustment measured by the added value of tertiary industry divided by the added value of secondary industry	0.0425471	0.373904	−0.640458	1.61385
ln*Pgdp*	Economic level calculated by the per capita gross domestic product (GDP)	1.08232	0.6726267	−0.861590	2.7149
ln*Edu*	Education level calculated by the ratio of the number of high school students of the total population	−4.132194	0.3817331	−5.379941	−3.274441
ln*FDI*	Foreign investment level measured by the registered capital of foreign-invested enterprises	10.66716	1.456547	6.55108	14.46964
ln*Wag*	Wage level measured by the average wage (yuan) of urban staff and workers on duty	10.54004	0.5599521	9.380505	11.91734

Std. Dev. refers to standard deviation
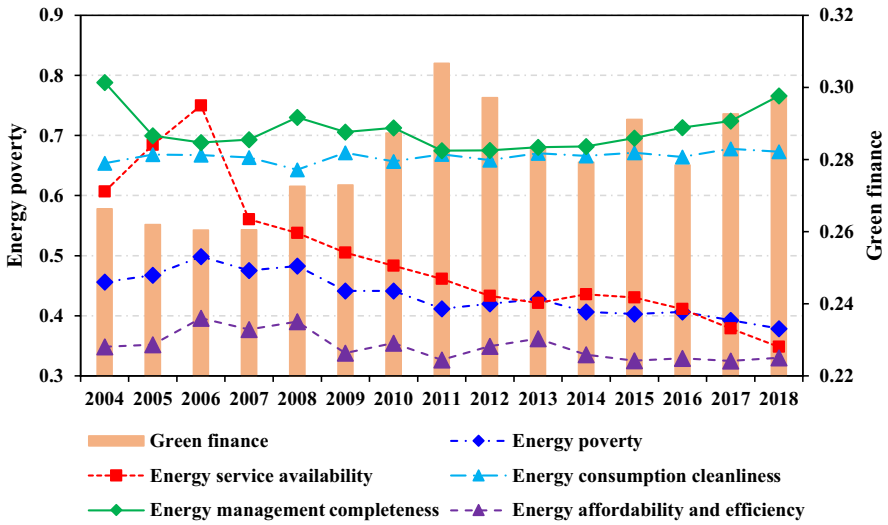
Fig. 1 Time trend of the average values of green finance and energy poverty

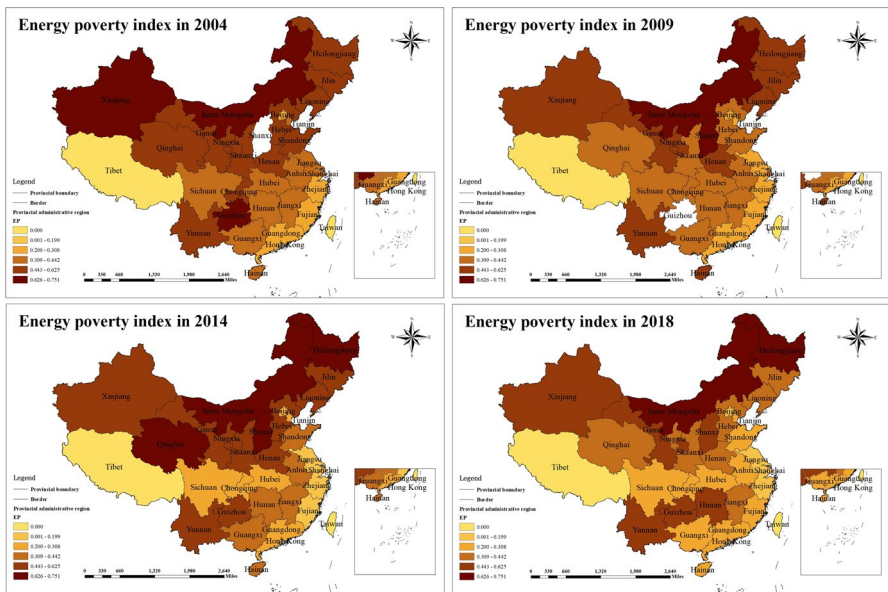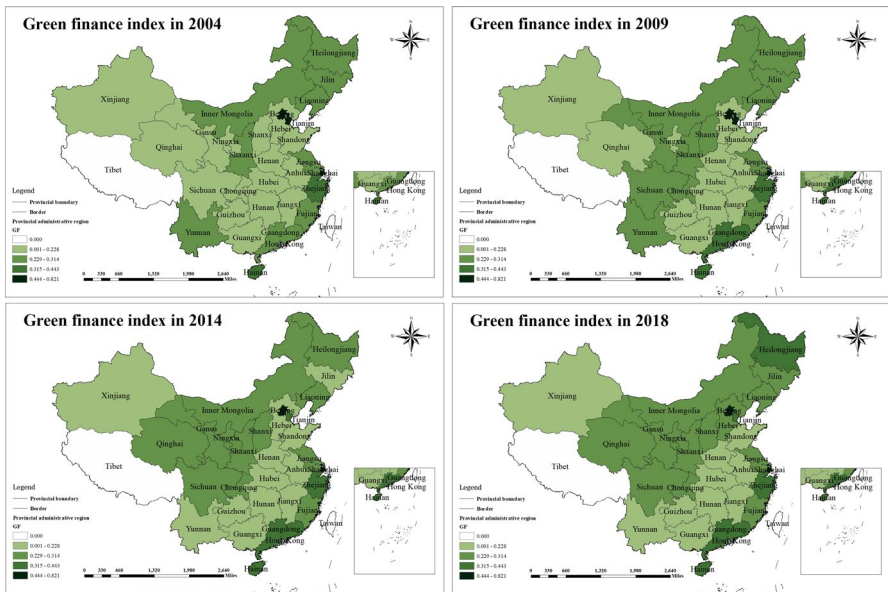**Fig. 2** Spatial distribution of China's energy poverty index in selected years

poverty, we also build a comprehensive system for China's energy finance that incorporates economy, finance, and the environment (Jiang et al. 2020) (see Table A2). To be specific, three indicators are included in economy and eight indicators are included in finance, respectively, and environment consists of six indicators. By

Table 2 Results of correlation checks

Variable	ln*EPI*	ln*GFI*	ln*Tec*	ln*Ind*	ln*Pgdp*	ln*Edu*	ln*FDI*	ln*Wag*
ln*EPI*	1.0000							
ln*GFI*	−0.4395[*]	1.0000						
	(0.0000)							
ln*Tec*	−0.6427[*]	0.2886[*]	1.0000					
	(0.0000)	(0.0000)						
ln*Ind*	−0.2765[*]	0.5519[*]	0.0749	1.0000				
	(0.0000)	(0.0000)	(0.1125)					
ln*Pgdp*	−0.5794[*]	0.5587[*]	0.7590[*]	0.4076[*]	1.0000			
	(0.0000)	(0.0000)	(0.0000)	(0.0000)				
ln*Edu*	−0.4055[*]	0.4356[*]	0.5806[*]	0.2481[*]	0.7336[*]	1.0000		
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)			
ln*FDI*	−0.7185[*]	0.4736[*]	0.8602[*]	0.1688[*]	0.7392[*]	0.5999[*]	1.0000	
	(0.0000)	(0.0000)	(0.0000)	(0.0003)	(0.0000)	(0.0000)		
ln*Wag*	−0.4082[*]	0.4125[*]	0.6283[*]	0.4985[*]	0.9100[*]	0.6002[*]	0.5167[*]	1.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	

[*]refers to $p < 0.05$, and the data in parentheses denote the p value of the correlation test

Fig. 3 Spatial distribution of China's green finance index in selected years

using the same improved entropy method, we calculate the provincial green finance composite index for the period 2004–2018. Notably, the sample data on economy were collected from CSY (2021), and the China Environment Statistical Yearbook

and China Regional Financial Operation Report provide data on the environment and finance, respectively.

The time trend of average green finance is shown in the histogram in Fig. 1. We find that the average composite index of green finance shows a significant trend of fluctuation during the sample period and reaches its peak in 2011, and green finance has been on the rise from 2016 to 2018. More importantly, the spatial distribution of green finance is shown in Fig. 3. Notably, the green development level of the financial industry in the prosperous eastern coastal provinces and northern provinces is obviously better than it is the central provinces.

4.2.3 Control variables

In addition to energy poverty and green finance, a series of control variables are introduced in our econometric model, and the specific measures are as follows:

Technical progress (*Tec*) is assessed by the number of domestic patent applications authorized, industrial structure adjustment (*Ind*) is calculated by the added value of tertiary industry divided by the added value of secondary industry; economic level (*Pgdp*) is assessed by per capita gross domestic product (GDP); education level (*Edu*) is evaluated by the ratio of the number of high school students of the total population; foreign investment level (*FDI*) is assessed by the registered capital of foreign-invested enterprises (in million US dollars); and wage level (*Wag*) is calculated by the average wage (yuan) of urban staff and workers on duty. The provincial data on technical progress, industrial structure adjustment, economic level, education level, foreign
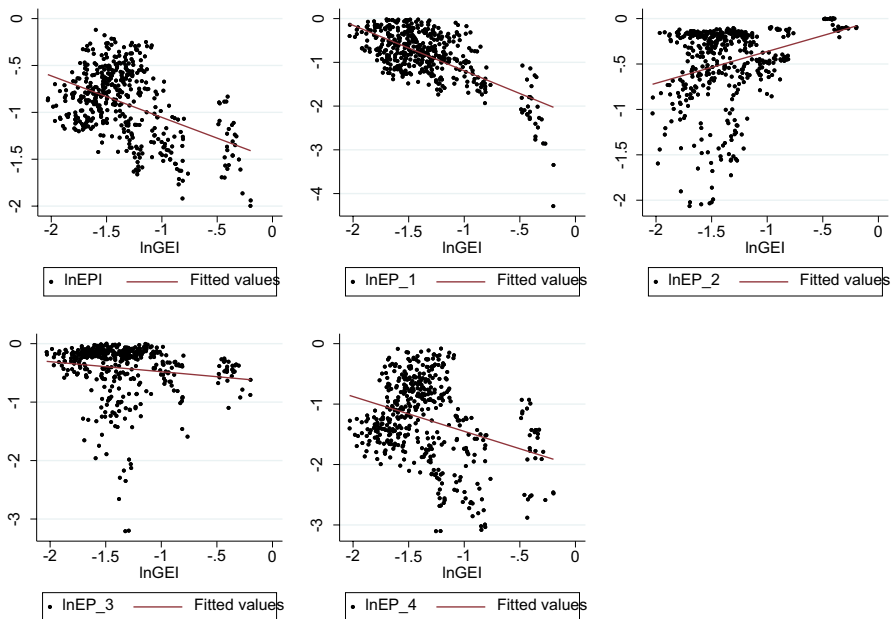

Fig. 4 Trend chart of the correlation between green finance and energy poverty

investment level, and wage level are obtained from CSY (2021), and Table 1 lists the definitions and descriptive statistics of all the variables used.

5 Empirical findings

5.1 Preliminary analysis

Prior to the benchmark estimates, we first check the correlation between variables (see Table 2). Obviously, the coefficients of green finance, technical progress, economic level, education level, foreign investment level, and wage level are all negative. Also, Fig. 4 shows the scatter plot between green finance (i.e., ln*GFI*) and energy poverty (i.e., ln*EPI*), which implies a negative role of green finance in eradicating energy poverty. In summary, the above correlation analysis provides preliminary findings for the positive energy poverty eradication effect of green finance development in China. Notably, to effectively assess the potential role of green development of China's financial industry in eradicating energy poverty, it is necessary to select more complicated and accurate empirical econometric models.

5.2 Benchmark estimates

Table 3 presents the estimated results of the panel random effect (RE), panel feasible generalized least squares (FGLS), Diff-GMM, and Sys-GMM methods simultaneously. Notably, before analyzing the benchmark findings, we find that the autocorrelation and overidentification tests are passed due to the significance of AR (1), AR (2), and the Sargan test. In this table, regardless of the static panel estimates or dynamic panel estimates, the coefficient values of green finance are significantly negative. This provides a robust regression result for green finance to help eradicate energy poverty.

   More specifically, the estimated results of Sys-GMM indicate that the coefficient of green finance (i.e., ln*GFI*) is −0.308, which emphasizes that improved development of green finance is negatively associated with energy poverty; put differently, increased green finance is a powerful weapon to eradicate energy poverty. The reasons may be that the green transition of the financial industry, on the one hand, can effectively guide investments to support the infrastructure establishment of natural gas and clean energy, strengthen energy supply, and improve the availability of energy consumption for residents. In addition, the gradual evolution of green finance facilitates the development of the non-thermal power industry, and strengthens the transformation of the current energy structure towards modernization, thus accelerating the eradication of fuel poverty (Rasoulinezhad and Taghizadeh-Hesary 2022). In the post-COVID-19 era, as all industries are affected, the gradual investment of financial industry in environmental technologies has obviously stimulated the greening and modernization of the economy, and the increasingly clean energy sector has provided a realistic guarantee for the green economic recovery. On the other hand, while promoting the growth of the clean energy industry, the green investment of financial institutions can also

Table 3 Estimated results of the impact of green finance on energy poverty

Explained variable: ln*EP*

Variable	Static panel estimation		Dynamic panel estimation	
	Panel RE	Panel FGLS	Diff- GMM	Sys-GMM
ln$EPI_{i,t-1}$			0.088***	0.462***
			(2.70)	(10.94)
ln*GFI*	−0.172***	−0.199***	−0.281***	−0.308***
	(−2.79)	(−4.78)	(−7.60)	(−7.95)
ln*Ind*	−0.097**	−0.155***	−0.127**	−0.219***
	(−1.98)	(−5.16)	(−2.28)	(−4.63)
ln*Tec*	−0.044*	−0.106***	−0.064***	−0.063***
	(−1.95)	(−8.23)	(−3.68)	(−4.38)
ln*Pgdp*	−0.241**	−0.182***	−0.181	−0.205**
				(−1.96)
	(−2.46)	(−2.78)	(−1.34)	
ln*Edu*	0.417***	0.180***	0.223**	−0.019
	(7.02)	(3.28)	(2.25)	(−0.21)
ln*FDI*	−0.045**	−0.010	0.052***	−0.004
	(−2.16)	(−0.84)	(4.37)	(−0.33)
ln*Wag*	0.082	0.216***	0.062	0.295***
				(2.68)
	(0.91)	(3.48)	(0.38)	
_Cons	0.875	−1.405**	−0.672	−3.236***
	(1.00)	(−2.19)	(−0.39)	(−2.73)
Wald test		815.66***		
Wooldridge test		30.570***		
BP LM test		1471.75***		
AR (1)			0.0025	0.0000
AR (2)			0.3628	0.7740
Sargan test			0.9993	0.9999

***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate the z-statistics

strengthen the completeness of management facilities of related industries, facilitate green innovation, and mitigate the deterioration of the environment, thus alleviating energy poverty and facilitating the green recovery of the economy.

Regarding the control variables, industrial structure adjustment, technical progress, and improved economic level can help eradicate energy poverty; this is basically consistent with the findings of Dong et al. (2021b). Adjusting the current industrial structure can effectively accelerate the transition from the secondary industry dominated by heavy industry to a green high-tech secondary and tertiary industry, which will not only strengthen the concentration of the population and resources, but also stimulate the development of the renewable energy industry. More importantly, technical

progress can significantly eliminate outdated polluting technologies, reduce fossil energy use, and improve energy efficiency, thus alleviating energy poverty (Tu and Rasoulinezhad 2021). In addition, the strengthening economic level can lay a solid economic foundation for the rapid evolution and technological innovation of the country's clean energy industry. However, rising levels of education and household wages are not conducive to eradicating energy poverty, which is contrary to our expectations. For education, the zero effect may reflect the fact that the education does not include sufficient sustainability-related elements. For wages, the positive wage–energy poverty nexus might be linked to the so-called rebound effect.

5.3 Robustness tests

5.3.1 Robustness test 1: estimation of the four indexes of energy poverty

To empirically check the robustness of the negative green finance–energy poverty nexus, we first re-estimate Eq. (2) by applying the four indexes of energy poverty (i.e., lnEP_1, lnEP_2, lnEP_3, and lnEP_4) to replace the composite index of energy poverty (i.e., lnEPI) by using the Sys-GMM technique; the corresponding estimates are shown in Table 4. The coefficient of green finance in the first, third, and fourth columns of Table 4 is significantly negative, while regarding lnEP_2, the coefficient of green finance is positive. This implies that the rapid development of green finance can alleviate energy poverty in terms of energy access capability, the completeness of the energy infrastructure, and energy efficiency & resident afford-ability, but has little effect on poverty alleviation in terms of energy cleanliness. In

Table 4 Robustness check 1: estimation of sub-indexes of energy poverty

Variable	lnEP_1	lnEP_2	lnEP_3	lnEP_4
ln$EP\_1_{i,t-1}$	0.406***			
	(26.68)			
ln$EP\_2_{i,t-1}$		0.614***		
		(28.56)		
ln$EP\_3_{i,t-1}$			0.505***	
			(42.03)	
ln$EP\_4_{i,t-1}$				0.581***
				(14.22)
lnGFI	−0.406***	0.404***	−0.511***	−0.378***
	(−7.80)	(13.13)	(−12.90)	(−6.08)
Control variables	Yes	Yes	Yes	Yes
_Cons	0.048	5.361***	2.725***	−3.146*
	(0.08)	(4.90)	(3.75)	(−1.74)
AR (1)	0.0047	0.0073	0.0276	0.0001
AR (2)	0.0389	0.3437	0.4811	0.6265
Sargan test	0.9967	0.9837	0.8590	0.9188

*** and * refer to statistical significance at the 1% and 10% levels, respectively; the values in parentheses indicate the z-statistics

addition, the coefficients indicate that the positive alleviating effect of green finance on poverty in terms of availability, management completeness, and affordability can offset the inhibiting effect on cleanliness. Thus, local governments should strongly support the development of green finance to achieve the effect of killing two birds with one stone, that is, the coordinated development of green finance and energy poverty eradication. This verifies the robustness of the benchmark conclusion: green finance can effectively help alleviate energy poverty.

5.3.2 Robustness test 2: alternative measures of energy poverty

The widespread use of natural gas and the vigorous advocacy of electricity consumption are effective measures for addressing the problem of energy poverty (Dong et al. 2021b; Zhao et al. 2021a). Thus, in this section, we proceed to check the reliability of the estimated results by employing the alternative measures of energy poverty alleviation—replacing the composite index of energy poverty (i.e., lnEPI) with per capita electricity consumption (i.e., EC) and per capita natural gas consumption (i.e., NG) for econometric regression based on the FGLS and Sys-GMM techniques. The results are illustrated in Table 5. It can be found that the green evolution of the financial industry can facilitate the increase of household electricity and natural gas consumption, and the stimulus effect on natural gas is obviously better than that on electricity consumption. This finding also supports the negative linkage between green finance and energy poverty.

Table 5 Robustness check 2: alternative measures of energy poverty

Variable	Per capita electricity consumption		Per capita natural gas consumption	
	Panel FGLS	Sys-GMM	Panel FGLS	Sys-GMM
ln$EC_{i,t-1}$		0.558***		
		(19.76)		
ln$NG_{i,t-1}$				0.782***
				(19.43)
lnGFI	0.123***	0.277***	0.987***	1.244***
				(6.44)
	(2.70)	(3.56)	(4.87)	
Control variables	Yes	Yes	Yes	Yes
_Cons	6.060***	5.335**	1.902	4.363
	(7.38)	(2.54)	(0.40)	(0.74)
Wald test	2623.91***		3484.21***	
Wooldridge test	80.626***		131.465***	
BP LM test	15.99***		147.40***	
AR (1)		0.0014		0.0010
AR (2)		0.1087		0.2139
Sargan test		0.9968		0.9993

*** indicates statistical significance at the 1% level; the values in parentheses indicate t-statistics

5.3.3 Robustness test 3: alternative estimation technique

In this section, we further verify the robustness by using the alternative estimated technique—the instrumental variable (IV) strategy proposed by Lewbel (2012). It is worth noting that this method mainly examines the causal relationship between green finance and energy poverty in China by constructing an instrumental variable based on heteroscedasticity in the random disturbance term (i.e., ε_{it}). We report the regression results of Lewbel's (2012) IV method in Table 6, and find that the potential effect of green finance on energy poverty and its four sub-indexes are consistent with the benchmark regression results, which significantly proves the robustness and reliability of the negative green finance–energy poverty nexus.

5.4 Provincial heterogeneous analysis

The provincial spatial distribution of green finance and energy poverty shows that significant regional heterogeneity exists in China's green finance and energy poverty across different provinces. Thus, to comprehensively and accurately assess the differential impact of China's green finance in eradicating energy poverty, we first divide the whole sample into high energy poverty (high EPI) areas, low energy poverty (low EPI) areas, high green finance (high GFI) areas, and low green finance (low GFI) areas according to the mean values of energy poverty and green finance in every province in 2018; the specific provinces of high EPI, low EPI, high GFI, and low GFI are shown in Table A3.

After the division of areas, we further evaluate the potential effect of green finance in eradicating energy poverty in different areas, and present the corresponding results in Table 7. In the high EPI area, the coefficient is 0.093, while in the low EPI area, the coefficient is − 0.225. This implies that the green transformation of financial institutions can effectively alleviate energy poverty in low EPI areas, but the effect on energy poverty eradication in high EPI areas is not obvious enough. From the spatial pattern of energy poverty, the low EPI areas are distributed mainly in economically prosperous provinces. The strong economic foundation can guarantee an improved financial system in these provinces and contribute to the alleviation of energy poverty. However,

Table 6 Robustness check 3: alternative estimation technique

Variable	ln*EPI*	ln*EP_1*	ln*EP_2*	ln*EP_3*	ln*EP_4*
ln*GFI*	− 0.097[**]	− 0.464[***]	0.350[***]	− 0.098[***]	− 0.161[*]
	(− 2.00)	(− 8.00)	(5.03)	(− 2.11)	(− 1.66)
Control variables	Yes	Yes	Yes	Yes	Yes
_Cons	1.317[***]	− 0.070	2.062[***]	− 2.010[***]	3.827[***]
	(5.27)	(− 0.22)	(6.97)	(− 6.16)	(8.18)
Unc_R^2	0.9360	0.9035	0.6768	0.6892	0.8960
Hansen J	0.000	0.000	0.000	0.000	0.000

[***], [**], and [*] indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate t-statistics

Table 7 Estimated results of the regional heterogeneous analysis

Explained variable: lnEP

Variable	Energy poverty		Green finance		Geographical location		
	High-EP	Low-EP	High-GF	Low-GF	Eastern	Central	Western
lnGFI	0.093***	-0.225***	-0.319***	-0.202***	-0.317***	0.063	-0.061
	(3.21)	(-10.98)	(-9.44)	(-5.94)	(-10.20)	(0.88)	(-1.30)
lnInd	-0.033	-0.158***	-0.150***	-0.090***	0.045	-0.058	-0.155***
	(-1.44)	(-5.20)	(-3.95)	(-3.66)	(1.20)	(-1.11)	(-2.72)
lnTec	-0.067***	-0.092***	-0.059***	-0.081***	-0.016	-0.063**	-0.088***
	(-6.65)	(-11.18)	(-3.94)	(-6.36)	(-1.58)	(-2.27)	(-5.23)
ln$Pgdp$	0.042	-0.078*	-0.284***	-0.206***	-0.688***	-0.314***	0.112
	(0.98)	(-1.75)	(-3.72)	(-3.87)	(-9.20)	(-2.57)	(1.62)
lnEdu	-0.084**	0.136***	0.382***	0.117***	0.568***	0.120	-0.063
	(-2.37)	(3.48)	(5.73)	(2.69)	(18.33)	(1.58)	(-1.37)
lnFDI	-0.005	-0.009	-0.028**	-0.024**	0.054***	-0.097***	-0.002
	(-0.44)	(-0.99)	(-2.03)	(-2.56)	(6.69)	(-2.91)	(-0.15)
lnWag	0.053	0.094***	0.158**	0.254***	0.201***	0.403***	-0.018
	(1.06)	(2.63)	(2.01)	(4.68)	(3.19)	(3.46)	(-0.23)
_Cons	-0.777	-0.747*	-0.163	-2.115***	-0.872	-2.534**	-0.191
	(-1.26)	(-1.93)	(-0.18)	(-3.84)	(-1.37)	(-2.32)	(-0.23)
Wald test	372.99***	241.69***	11.247***	402.27***	72.88***	138.88***	107.33***
Wooldridge test	19.047***	17.628***	133.32***	18.223***	7.715**	34.880***	12.764***
BP LM test	149.62***	332.18***	393.06***	700.64***	313.07***	138.41***	432.07***

***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate the z-statistics

in high EPI areas, economic development is backward, the financial systems are relatively incomplete, and the alleviating effect of energy poverty is limited. In addition, green finance has a positive correlation with energy poverty alleviation in both high and low GFI areas, and the alleviating effect of energy poverty in high GFI areas of China is more significant than that in low GFI areas.

In addition, we divide the full sample into eastern, central, and western regions based on geographical location with reference to the classification standards of the National Bureau of Statistics of China; the estimated results are reported in the last three columns of Table 7. We find that green finance can effectively contribute to energy poverty alleviation only in the eastern provinces. Against the current background, it is clear that the huge economic base, complete financial institutions, superior geographical location, and convenient transportation conditions of the eastern provinces can provide a sufficient basis and reasonable opportunities for energy poverty alleviation.

6 Further discussion on the mediation effects

6.1 Model construction

After conducting the benchmark estimates on the green finance–energy poverty nexus and analyzing the regional heterogeneity, we examine in greater depth how green finance alleviates energy poverty, which can provide new ideas for further discussion on green economic recovery in the post-COVID-19 era from the perspective of green finance. In the benchmark estimates, technical progress and industrial structure adjustment have a particularly significant stimulating effect on fuel poverty eradication; accordingly, we attempt to discuss the mediating role of these two variables in affecting the green finance–energy poverty nexus. In this regard, the mediating effect model is a wise choice to deal with such problems, and the specific equations of the mediating effect model are constructed as follows:

$$\ln EPI_{it} = \varphi_0 + \varphi_1 \ln EPI_{i,t-1} + \varphi_2 \ln GFI_{it} + \sum_{k=3}^{6} \varphi_k \ln X_{it} + \eta_i + v_t + \varepsilon_{it} \quad (4)$$

$$\ln M_{it} = \xi_0 + \xi_1 \ln M_{i,t-1} + \xi_2 \ln GFI_{it} + \sum_{k=3}^{6} \xi_k \ln X_{it} + \eta_i + v_t + \varepsilon_{it} \quad (5)$$

$$\ln EPI_{it} = \beta_0 + \beta_1 \ln EPI_{i,t-1} + \beta_2 \ln GFI_{it} + \beta_3 \ln Tec_{it} + \beta_4 \ln Ind_{it} + \sum_{k=5}^{8} \beta_k \ln X_{it} + \eta_i + v_t + \varepsilon_{it} \quad (6)$$

where φ_0 and ξ_0 refer to the constant terms, and $\varphi_k(k = 1, 2, ..., 6)$ and $\xi_k(k = 1, 2, ..., 6)$ represent the coefficients that need to be assessed. M indicates technical progress and industrial structure adjustment. The variables and parameters are consistent with Eq. (2). Notably, only when green finance significantly affects

energy poverty, that is, the coefficient of green finance in Eq. (4) (i.e., φ_2) is significant, can we further test the direct and indirect effects in the mediating effect model. Furthermore, the coefficient of green finance in Eq. (6) refers to the direct role of green finance on energy poverty, and only when the coefficients of green finance in Eq. (5) and technical progress as well as industrial structure adjustment in Eq. (6) are all significant can the existence of indirect effect be confirmed. The product of the coefficients (i.e., $\xi_2\beta_3$ and $\xi_2\beta_4$) indicates the magnitude of the indirect effect of technical progress and industrial structure adjustment, respectively.

6.2 Results and discussion

By applying the Sys-GMM strategy, we estimate Eqs. (4)–(6) and report the empirical results in Table 8. In the first column of this table (i.e., Model (1)), we find that

Table 8 Estimated results of the mediation effects

Variable	Model (1)	Model (2)		Model (3)
	Total effect	Technical effect	Structure effect	Direct effect
$\ln EPI_{i,t-1}$	0.519***			0.462***
	(24.30)			(10.94)
$\ln Tec_{i,t-1}$		0.734***		
		(47.80)		
$\ln Ind_{i,t-1}$			0.918***	
			(31.31)	
$\ln GFI$	−0.383***	0.370***	0.020*	−0.308***
	(-9.09)	(5.76)	(1.78)	(−7.95)
$\ln Tec$				−0.063***
				(−4.38)
$\ln Ind$				−0.219***
				(−4.63)
$\ln Pgdp$	−0.012	0.064	−0.252***	−0.205**
	(−0.18)	(0.77)	(−10.45)	(−1.96)
$\ln Edu$	0.134***	0.419***	0.279***	−0.019
	(2.87)	(3.51)	(13.11)	(−0.21)
$\ln FDI$	−0.054***	0.097***	0.016**	−0.004
	(−3.78)	(10.51)	(2.28)	(−0.33)
$\ln Wag$	−0.056	0.104	0.208***	0.295***
	(−0.87)	(1.57)	(7.08)	(2.68)
_Cons	0.778	2.590***	−0.886***	−3.236***
	(1.03)	(2.75)	(−2.76)	(−2.73)
AR (1)	0.0000	0.0000	0.0055	0.0000
AR (2)	0.4532	0.1999	0.7073	0.7740
Sargan	0.9917	0.9846	0.2654	0.9999

***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate the z-statistics

the coefficient of green finance is -0.383, which indicates the empirical results of the total effect of green finance on eradicating energy poverty. Furthermore, Model (2) presents the potential effects of green finance on technical progress and industrial structure adjustment. In these two columns, the estimated coefficients of green finance in technical effect and structure effect are 0.370 and 0.020, respectively. This implies that: (1) the green transformation of the financial industry can strengthen regional technical innovation activities and accelerate the process of industrial structure adjustment; (2) the stimulating effect of green finance on technical innovation is significantly greater than that on promoting industrial transformation. Against the background of the steady progress of green finance policies, the rapid development of the green finance industry actively invests in economic activities that prevent environmental degradation and conserve resources, effectively guides the transfer of limited resources from high-polluting industries to low-polluting industries, and accelerates the process of technical activities and industrial structure adjustment.

The coefficient of green finance in Model (3) is − 0.308, which denotes the direct effect of green finance on energy poverty. Furthermore, the estimated coefficients of technical progress and industrial adjustment are − 0.063 and − 0.219, respectively. Thus, $\xi_2 * \beta_3 = 0.370 * (-0.063) = -0.0233$ and $\xi_2 * \beta_4 = 0.020 * (-0.219) = -0.0044$. This suggests that the contribution of technical progress in affecting the green finance–energy poverty alleviation nexus is $(\xi_2 * \beta_3)/\varphi_2 = -0.0233/ - 0.383 = 6.09\%$, and the contribution of industrial structure adjustment in total effect is $(\xi_2 * \beta_4)/\varphi_2 = -0.0044/ - 0.383 = 1.15\%$. This shows that technological progress and industrial adjustment, as pathways of green finance affecting energy poverty, have a mediation effect ratio of 6.09% and 1.15%, respectively. Hence, we can find that technological progress and industrial structure adjustment are effective channels for green finance to help energy poverty eradication, and the effect of technical innovation is obviously better than that of industrial transfer. However, the mediation proportion of the two channels is relatively small, and other influencing pathways may exist, which will be our future research direction.

Following the above discussions, we can conclude that the rapid evolution of green finance not only directly contributes to energy poverty eradication, but also helps alleviate energy poverty by accelerating technical innovation activities and the gradual optimization and upgrading of the current industrial structure. In summary, the specific influence mechanism between green finance and energy poverty alleviation is shown in Fig. 5.

7 Conclusions and policy suggestions

To empirically investigate whether green finance vigorously advocated by local governments is conducive to alleviating China's current energy poverty and promoting the green economic recovery in the post-COVID-19 era, we examine the dynamic green finance–energy poverty nexus by applying provincial sample data for the period 2004–2018. Furthermore, this study further explores the potential regional heterogeneity across different regions and the mediating effects of technical progress and industrial structure adjustment. The primary findings are presented as follows:
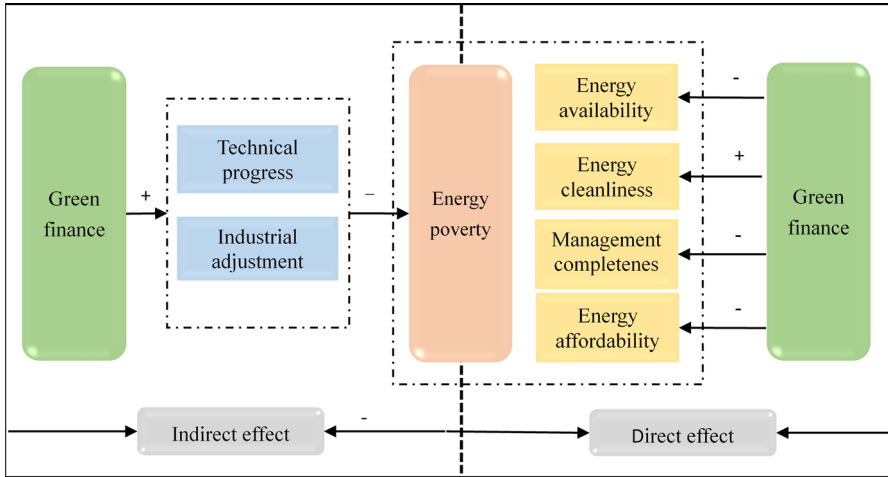
Fig. 5 The influence mechanism between green finance and energy poverty

First, the main conclusion of this study is related to the negative green finance–energy poverty nexus. The estimated results of the benchmark regression report that the coefficient of green finance is − 0.308, which suggest that the rapid promotion of green finance can effectively facilitate poverty eradication and accelerate green recovery of the economy in the post-COVID-19 era. This finding is also verified by a series of robustness tests.

Second, the analysis of provincial heterogeneity shows that green finance is negatively related to energy poverty in low energy poverty areas, while in high energy poverty areas, improved green finance cannot contribute to energy poverty eradication. A significant negative correlation between green finance and energy poverty exists in high and low energy poverty areas. In addition, green finance can only eradicate energy poverty in the eastern regions.

Third, from the analysis of the mediating effect model we find that green finance not only helps eradicate China's energy poverty directly, but also indirectly facilitates energy poverty alleviation by accelerating technical innovation activities and adjusting industrial structure.

The discussion on the green finance–energy poverty nexus in this study provides an effective reference for alleviating existing energy poverty and facilitating green economic recovery. Based on the negative relation between green finance and energy poverty, we develop the following policy implications.

First, the primary finding highlights the important role of China's green finance in facilitating energy poverty alleviation and accelerating the green economic recovery in the post-COVID-19 era. Accordingly, continuing to vigorously advocate the green transformation of financial institutions and formulate relevant policies and regulations to promote the green evolution of the financial industry is crucial. Currently, green finance has become a vital pillar of the green economy. To effectively achieve a win–win situation of continuous green evolution of finance and energy poverty eradication, on the one hand, local governments should set up provincial green

finance-development institutions. For instance, Gansu and Guizhou provinces have successively established green finance innovation and development-leading groups. Establishing a strong regional leadership center can effectively enhance high-level design. In addition, the formulation of a construction plan for a green finance system can send a positive signal to society that the government focuses on green finance, so as to clarify the goals and tasks of relevant departments and institutions in green finance. Financial regulators should also provide basic guarantees for increasing the growth of green finance. A positive incentive mechanism to facilitate the development of green finance, establishing and improving relevant systems of green credit and green insurance, and strengthening theoretical research and publicity related to green finance are all effective strategies to facilitate the green evolution of the financial industry.

Second, our results highlight the regional heterogeneity of green finance in energy poverty alleviation. In other words, significant differences in the effects of green finance exist across different regions. Therefore, when local governments actively formulate relevant strategies to promote the green evolution of finance, they should implement them in more detail, according to the local actual situation. For example, in the prosperous eastern coastal provinces, provincial governments should strengthen theoretical research on green finance and set an example for other provinces. However, in the underdeveloped central and western regions, strengthening the infrastructure construction of green finance and improving the financial institution system are more effective measures.

Third, the mediating role of technical progress and industrial optimization between green finance and energy poverty can improve the current situation of energy poverty in China. Therefore, local governments should provide financial and policy support to enterprises actively carrying out green technical innovation, and effectively solve the financial and institutional obstacles in the current process of enterprise transformation. At the same time, local governments should vigorously advocate and publicize green economic transformation and facilitate the increasing infiltration of the concept of green economic development. In addition, strengthening the rapid growth of the clean energy industry will not only facilitate the optimization and upgrading of the industry, but will also reduce the dependence of residents and enterprises on highly polluting fossil energy, thus achieving a win–win situation of green finance and energy poverty alleviation.

The current research on the green finance–energy poverty nexus only assesses the potential role of the evolution of green finance in eradicating energy poverty in China, research gaps still exist. One is associated with the research sample. In our study, we only check whether the development of green finance can help eradicate energy poverty in China, it is necessary for us to explore the nexus in other economies, especially in the global case. Another shortcoming is related to influencing mechanism. The underlying effects of technical progress and industrial adjustment are explored by using the mediation effect model; other influencing channels such as energy consumption structure and financial structure also deserve further discussion.

Appendix

See Tables 9, 10, 11 and 12.

Table 9 The specific indicator system of energy poverty in China

First-level indicator	Second-level indicator	Measure	Code	Property
Energy access capability	Residential energy consumption	Per capita electricity consumption (kWh/person)	x1	+
		Per capita natural gas consumption (Cubic meters/person)	x2	+
	Energy supply	Urban gas penetration rate	x3	+
		Urban per capita natural gas supply (Cubic meters/person)	x4	+
Energy cleanliness	Energy decarbonization	The proportion of non-thermal power generation in electricity generation	x5	+
	Energy modernization	Biogas production per rural household (Cubic meters)	x6	+
Energy infrastructure completeness	Energy management infrastructure	Average number of staff in rural energy management extension agencies	x7	+
	Energy investment	Per capita fixed assets of state-owned electric power, steam, and hot water production and supply industries	x8	+
Energy efficiency and resident affordability	Energy equipment	Air conditioners per hundred urban households	x9	+
		Refrigerators per hundred urban households	x10	+
		Number of range hoods per hundred rural households	x11	+
	Living energy pollutant emissions	Per capita sulfur dioxide emissions from residential sector (tons/person)	x12	–
		Per capita soot emissions from residential sector (tons/person)	x13	–

Table 10 The indicator system of green finance in China

Dimension	Specific indicators	Measure	Code	Property
Economy	Per capita GDP	GDP/population	×1	+
	Per capita disposable income	Disposable income/population	×2	+
	Unemployment rate	Unemployed/total labor force	×3	-
Finance	Per area banks	Amount of banks/areas	×4	+
	Per area bank staff	Amount of bank staff/areas	×5	+
	Per capita banks	Amount of banks/population	×6	+
	Per capita bank staff	Amount of bank staff/population	×7	+
	Deposits	Deposits/GDP	×8	+
	Loans	Loan/GDP	×9	+
	Density of insurance	Premium/population	×10	+
	Depth of insurance	Premium/GDP	×11	+
Environment	The rate of wastewater	Wastewater/(deposit + loan)	×12	−
	The rate of sulfur dioxide	Amount of sulfur dioxide/(deposit + loan)	×13	−
	The rate of solid waste	Amount of solid waste/(deposit + loan)	×14	−
	The rate of energy consumption	Amount of energy consumption/(deposit + loan)	×15	−
	The rate of nature reserve	Amount of nature reserve/(deposit + loan)	×16	+
	The rate of forest	Amount of forest/(deposit + loan)	×17	+

Table 11 The specific provinces of the different regions

Category	Region	Provinces
Energy poverty	High EPI (13 provinces)	Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Hunan, Guizhou, Yunnan, Shaanxi, Gansu, Ningxia, and Xinjiang
	Low EPI (17 countries)	Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, and Qinghai
Green finance	High GFI (10 provinces)	Beijing, Tianjin, Inner Mongolia, Liaoning, Heilongjiang, Shanghai, Zhejiang, Guangdong, Hainan, and Gansu
	Low GFI (20 provinces)	Hebei, Shanxi, Jilin, Jiangsu, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Qinghai, Ningxia, and Xinjiang
Geographical location	Eastern region (11 provinces)	Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan
	Central region (8 provinces)	Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan
	Western region (11 provinces)	Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang

Table 12 Abbreviations list

Abbreviations			
CESY	China Energy Statistical Yearbook	IEA	International Energy Agency
CFPS	China Family Panel Studies	IV	Instrumental variable
CSY	China Statistical Yearbook	R&D	Research and development
Diff-GMM	Differential GMM	RE	Random effect
FGLS	Feasible generalized least squares	SDGs	Sustainable Development Goals
GDP	Gross domestic product	Sys-GMM	System GMM
GMM	Generalized method of moments		

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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