



The impact of green finance development on energy poverty: Does climate risk matter?

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Abstract

Energy poverty (EP) presents a significant challenge to the global energy system while also hindering sustainable development in various countries. Based on an evaluation indicator system of EP, this paper explores whether green finance (GF) significantly alleviates EP in 30 provinces of China using the method of moment estimation quantile regression (MMQR), and investigates how climate risks affect the relationship between GF and EP. The findings are as follows: (1) GF has a significant alleviating effect on EP. It can provide funding and support for sustainable energy and energy efficiency projects, thereby improving people's energy supply and utilization. GF can alleviate EP at all quantiles, but the degree of alleviation varies. (2) Climate risks have a significant moderating effect on the negative relationship between GF and EP. However, the moderating effect is only significant at the 25th and 50th quantiles. This means that the alleviating effect of GF on EP is severely affected by climate risks, which is more prevalent in provinces with lower and medium EP. (3) This moderating effect indicates the existence of spatial heterogeneity, mainly in the western regions of China. Our findings offer guidance for attaining sustainable energy development and targeted EP reduction.

Keywords Green finance · Energy poverty · Climate risk · MMQR

1 Introduction

Global warming poses a serious threat to human societies and natural ecosystems, with significant impacts on the living environment, business operations, and economic development (Lee & Lee, 2022). Rapid urbanization and economic expansion have led to severe environmental degradation due to the overuse of energy and natural resources (Muhammad et al., 2021). China has made considerable progress in reducing emissions and conserving energy recently. However, security and energy use remain major obstacles (Zhao

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et al., 2014). Energy poverty (EP) has drawn the attention of society and scholars (Lee et al., 2022; Shi et al., 2022; Siksnyte-Butkiene et al., 2021). The availability of reasonably priced, trustworthy, and contemporary energy services is a vital issue for many households and communities worldwide. According to IEA data, 840 million people worldwide need access to modern energy services, most of whom reside in underdeveloped regions of Africa and Asia. In the absence of contemporary energy, locals frequently use conventional fuels (such as coal and firewood) for lighting, heating, and cooking. This leads to low efficiency and high indoor air pollution, which raises the risk of disease and illness. The IEA's World Energy Outlook 2004 highlights how urgent it is to deal with EP.

EP has attracted widespread attention from scholars. The research indicates that Environmental Pollution (EP) is associated with social issues such as gender inequality, environmental pollution, market systems, and policies. At the same time, some scholars focus on the impact of EP and potential solutions, including improving energy services, promoting renewable energy, and energy efficiency technologies. Green Finance (GF) has gradually become a focal point in academic and governmental institutions and is recognized as an effective tool for addressing EP. GF supports sustainable development and climate change mitigation by providing financial support, innovative products, and services. It promotes the development of renewable energy and clean technologies, improves energy structure, and reduces the impact of EP (Liu et al., 2022). However, studies also highlight challenges for GF in addressing EP, such as the need for policy support, market promotion, and overcoming issues like information asymmetry and the lack of a credit evaluation system (Dong et al., 2022b; Kumar et al., 2022).

Climate risk is a significant challenge for Green Finance (GF) in mitigating energy poverty (EP). Climate risk is the uncertainty caused by extreme weather events such as floods, droughts, tsunamis, and long-term climate changes. Research indicates that climate change and related extreme weather events significantly threaten GF's effectiveness (Kliuchnikov & Kliuchnikov, 2021; Nawaz et al., 2021). Climate risk may lead to increased investment costs and losses in GF projects, including damage to green energy equipment such as solar panels and wind turbines, resulting in investor losses. Extreme weather events, like floods, droughts, and hurricanes, can disrupt the production and distribution of renewable energy technologies, causing delays and cost overruns (Perera et al., 2020). This may reduce the attractiveness of GF investments for investors.

Additionally, climate risk may increase maintenance and replacement costs for GF projects, affecting their profitability and hurting the financing of renewable energy projects. Extreme climate events may raise insurance costs and reduce coverage for renewable energy projects, making it more challenging for investors to secure financing, ultimately limiting the funding available for GF investments and impacting environmental pollution. Climate risks may also undermine the returns and sustainability of GF projects, particularly for green energy projects threatened by extreme weather events. Lastly, climate risks will affect energy supply and prices, significantly impacting energy poverty. For example, extreme heatwaves, as found by Chirambo (2018), can cause power outages, increase energy demand, and result in higher electricity prices, disproportionately affecting low-income households. This could exacerbate energy poverty, making it even more challenging for families to access affordable and reliable energy. Therefore, GF must carefully address climate risks when addressing EP.

The efficacy of Green Finance (GF) in addressing Energy Poverty (EP) is influenced by climate change risks. Governments and financial institutions must integrate climate risks into their investment decisions to overcome these challenges. This involves developing adaptation strategies to mitigate risks associated with extreme weather events and

supporting investments in resilient infrastructure and clean energy technologies. This paper seeks to provide fresh insights into whether and how GF impacts EP, particularly in the context of climate risks, and its potential to alleviate EP. Given significant variations in the distribution of energy resources across China's eastern, central, and western regions, there may be disparities in accessing modern energy services, leading to diverse effects of GF in the different areas (Dong et al., 2021; Jin et al., 2021; Zhao et al., 2021).

Most researchers investigating GF or EP often rely on linear analysis based on conditional means, which primarily explains the average effect of GF on EP and may encounter endogeneity issues. However, little is known about how climatic threats impact the relationship between the two at different quantile levels of EP. The effectiveness of GF in reducing EP varies significantly across different EP levels due to variations in funding, technology, related infrastructure, and green capacity development. Therefore, studying the distributional variability of how the connection between GF, climate hazards, and EP changes at various EP levels is crucial. This study employs the moment quantile regression (MMQR) model that Machado and Silva (2019) developed to illustrate how GF and climate hazards influence EP. This model surpasses the conventional linear regression approach by providing parameter values at various quantiles and allowing sensitive moment estimates for regression methods with individual effects, particularly in addressing endogeneity issues. This enhances the robustness of the empirical findings in this research and provides valuable policy guidance for diverse geographical areas.

This study's empirical findings show that GF significantly reduces EP since it may fund and support projects that increase people's access to and usage of sustainable energy. The MMQR results show that GF can reduce EP at all quantiles. However, the level of reduction varies. Second, empirical models that are both linear and nonlinear support the finding that climate hazards significantly moderate the negative association between GF and EP. Yet, only the 25th and 50th quantiles show a meaningful moderating effect. This indicates that the relieving effect of GF is significantly impacted when there is a considerable degree of uncertainty surrounding climate change. More often than not, provinces with low and moderate EP levels experience this predicament. Finally, this moderating impact shows that geographical heterogeneity exists in China, primarily in the west, and is not essential in the center, east, or northeast. Hence, for academics and governments, this study's findings offer valuable insights and policy suggestions.

This paper has four contributions. Firstly, most of the literature examines how RE technology innovation and EP are related or how they are related to other societal issues (such as gender inequality, environmental degradation, etc.). More research on the impact of GF on EP, which enriches the existing literature in this field, is needed. Secondly, unlike traditional linear regression methods, this paper uses the MMQR model proposed by Machado and Silva (2019) to solve the endogeneity problem, demonstrating the impact of GF on EP at different quantile levels and providing meaningful policy recommendations for other regions. Thirdly, scholars in the past have overlooked the role of climate risk in studying the impact of GF on RE or EP. We pay more attention to the negative moderating effect of climate risk. Last, we investigated the regional heterogeneity of GF's effects on EP and the moderating role of climate risk, offering specific suggestions for GF development in various places.

The paper is structured as follows. Section 2 provides the relevant literature and hypotheses. Section 3 presents the MMQR methodology and data. Section 4 analyses the empirical results. Section 5 contains conclusions and policy recommendations.

2 Literature review and hypothesis development

2.1 Research on EP

The existing literature on EP focuses on three aspects: the measurement of EP, the effects of EP, and how to eliminate EP. The first is on the measurement of EP. There are two main approaches to measuring EP: a single index and a composite index. A single index refers to measuring EP using a certain index or from a specific aspect (Dong et al., 2022b), while a composite index is mainly used to comprehensively assess EP by constructing a multidimensional composite index of EP (Pelz et al., 2018). In addition, scholars have also considered EP in China by constructing a comprehensive EP index system (Zhao et al., 2021), and it is found that EP in China shows a clear trend of alleviation. Second, the social-economic effects of EP. Scholars have focused on the impact of EP on the health of the population (Pan et al., 2021), economic growth (Doğanalp et al., 2021; Singh & Inglesi-Lotz, 2021), environmental improvement (Druică et al., 2019; Hassan et al., 2022), and employment and education (Apergis et al., 2022; Banerjee et al., 2021; Hassan et al., 2022) and other social factors. Thirdly, there are studies on how to eradicate EP. Scholars have mainly examined financial development (Dong et al., 2022b; Mohsin et al., 2022; Nguyen et al., 2021), marketisation processes (Wang et al., 2022b), individual carbon trading mechanisms (Parag & Strickland, 2010; Zhang et al., 2022), energy efficiency (Dong et al., 2022a; Li et al., 2021) and fiscal policy tools (Chien et al., 2022; Lakatos & Arsenopoulos, 2019), in terms of establishing effective measurement indicators and studying the social-economic aspects of EP. Bhutto and Karim (2007) argue that active development of clean energy, especially renewable energy, and accelerated diversification of energy resources can effectively combat EP. In addition, promoting electrification in rural areas (Banerjee et al., 2021), accelerating the development of natural gas infrastructure (Dong et al., 2021), improving energy efficiency (Dong et al., 2022a) and establishing individual carbon trading mechanisms (Zhang et al., 2022) are currently effective strategies to address EP.

Furthermore, Hashmi et al. (2022) studied the influencing factors of renewable energy consumption from the monetary policy perspective, finding that expansionary monetary policy would promote renewable energy consumption in both the long and short term, and vice versa. Furthermore, Bhowmik et al. (2023) employed a bootstrap autoregressive distributed lags (ARDL) method to explore the heterogeneous impact of three types of uncertainty—monetary, fiscal, and trade policy—on U.S. energy consumption. The study found that uncertainty in monetary policy inhibited energy consumption, while uncertainty in trade and fiscal policy drove the overall growth in energy consumption. Syed et al. (2023) based on the novel Fourier augmented ARDL approach, demonstrated that climate policy uncertainty would lead to a sharp decline in renewable energy consumption in the long and short term.

2.2 Research on the GF–EP nexus

Some academics believe that green financing will lessen EP. This is due to the fact that green financing can hasten the energy transition and economic development (Barua & Aziz, 2022; Wang et al., 2022a), reduce energy shortages, and make modern energy accessible to nations with less developed economies. For instance, Setyowati (2020) asserts that in order for Indonesia to reach its RE targets and offer electricity to residents of EP, the

country should mobilize the private sector to fund large-scale climate finance for RE generation. According to Azhgaliyeva et al. (2020), fossil fuel investment still accounts for the majority of energy investment, which may jeopardize the growth of green energy necessary to ensure energy security and satisfy climate and clean air targets. However, addressing various development concerns, such as reducing poverty, requires access to energy (Mushshed & Ozturk, 2023; Xu et al., 2019). Cheng and Taghizadeh-Hesary (2023) utilized the Fully Modified Ordinary Least Square model to investigate the relationship between GF and EP in 20 developing countries in Asia. The study revealed that increased GF investment would narrow the EP gap in these countries. Additionally, Zhang et al. (2023) examined the relationship between GF and EP from the perspective of economic policy uncertainty, demonstrating that the development of GF could effectively alleviate EP. However, economic policy uncertainty would hinder the EP reduction effects of GF.

Even though numerous experts have comprehensively summarized GF and its effects on the economy and environment, there are significant knowledge gaps. First, an increasing number of academics evaluate GF from various angles, but few evaluate its current level of growth, particularly in China. Second, despite the fact that several studies have examined the potential effects of GF evolution from various angles, pertinent research on the GF-EP nexus is still in the exploratory stage, and pertinent studies in China are still in short supply. It is also important to investigate how China's GF development may support the post-Coronavirus Disease 2019 (COVID-19) era's transition to a green economic recovery. Third, it is unknown how GF influences EP and, in particular, how it typically affects technical advancement and industrial restructuring. Filling in the above research gaps could help scholars and the government develop more precise solutions for GF to alleviate EP.

2.3 Theoretical framework and hypothesis

GF is regarded as an effective strategy to eradicate EP and raise population well-being because it provides efficient financial support for advancing environmentally friendly and sustainable development (Hou et al., 2022). On the one hand, the green financial system is an institutional setup where the state promotes resource efficiency and offers investment and financing support for clean energy development projects through financial instruments like green bonds, green funds, green insurance, and green credit to improve EP.

The GF further optimizes the distribution of social resources and modifies China's unequal energy distribution pattern, which is more concentrated in the North than in the South and more in the West than in the East, in accordance with the laws of the market economy and national macro-control. By implementing a green financial system, the government can integrate society's idle economic resources, solve the challenging problem of financing the market's new energy sector, direct market capital to clean energy businesses like photovoltaic power generation and encourage financial institutions to invest in renewable energy sources.

After receiving financial assistance, new energy businesses leverage the market, utilize capital to the fullest extent, increase the volume of new energy products they produce, increase the total supply of green electricity, etc., gradually displace traditional solid biomass and polluting fossil energy in the market, assist in resolving the EP problem, and alter the problem of energy scarcity, such as the lack of power in underdeveloped and remote areas. In contrast to established businesses, new energy industries are characterized by significant investment in research and development (R&D) and lengthy payback periods. The government has allowed energy companies to fund research, minimize the costs and

risks involved with its development, and maintain enterprises' and society's motivation to develop green technology by establishing a green financial system.

The establishment of a green financial system prevents money from amassing in conventional polluting industries, motivates traditional energy of fossil to transform, realizes transformational development through technological and industrial innovation, accelerates the development of a diversified energy supply system, recognizes the transition from a conventional fossil energy supplier to a comprehensive energy service provider, and gradually lowers the amount of money that is invested in traditional polluting industries.

Additionally, to address the energy shortage, new energy enterprises receive financial support through the use of the green financial system, increase new energy research and development, encourage technological innovation and industrial structure modernization, expand new energy varieties, adjust the pattern of energy supply and demand, realize energy system optimization, and improve all aspects of energy production, supply, management, and services (see Fig. 1).

Hypothesis 1: GF can alleviate EP.

Green finance can reduce energy poverty by supporting renewable energy and energy efficiency improvements, but the effectiveness of this reduction may be limited. On the one hand, green finance investments are mainly concentrated in relatively affluent regions and countries, and the energy supply situation in impoverished areas often remains unchanged. This may result in residents in poor regions facing energy poverty issues, even if the energy supply in the other provinces has improved. On the other hand, the sources and flow of green finance funds may result in uneven resource allocation. For example, some countries or organizations may issue green bonds in international markets to obtain funding for renewable energy

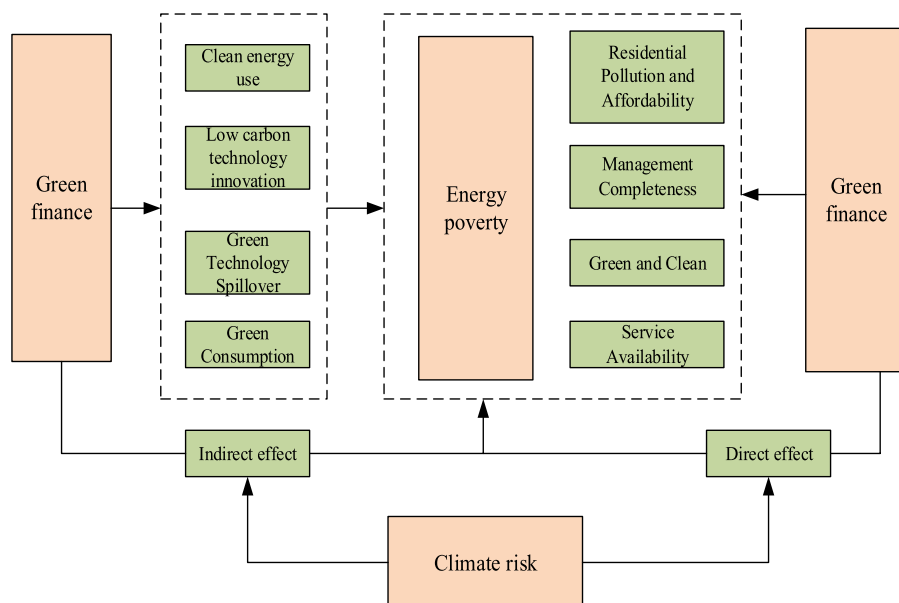


Fig. 1 The impact mechanisms between GF and EP

projects. Still, these funds may not necessarily flow to energy-poor areas. In addition, some energy-poor areas may face financing difficulties because their projects are considered high-risk or lack sufficient guarantees, making it difficult for green finance to enter these areas. Therefore, the impact of green finance on energy poverty may be asymmetrical, and improvements to energy supply in impoverished areas may be limited.

Hypothesis 2: Green finance may have an asymmetric impact on energy poverty.

The importance of climate risk is increasingly recognized when looking at the issue of GF, RE, and their linkages. Issues such as natural disasters, extreme weather, and environmental change caused by climate change may have serious impacts on energy infrastructure and services, which in turn may lead to an increase in EP. Firstly, climate change may affect the availability and distribution of energy. Natural disasters and climate extremes, such as floods, droughts, storms, and heat waves, can damage energy infrastructure, damaging facilities such as transmission lines, dams, and wind turbines, which in turn can lead to disruptions in energy supply and further impoverish those who already lack energy. Secondly, climate change may lead to higher energy costs. As factors such as extreme weather and natural disasters brought about by climate change may impact energy infrastructure, the cost of maintaining and repairing energy facilities will also increase. These costs may be passed on to consumers in the form of price increases, which in turn will expose the poor to higher energy costs. Finally, climate change may also have an impact on the stability and reliability of energy sources. In extreme weather conditions, such as heat, cold, and flooding, energy systems may face strains and be unable to meet people's energy needs. This may lead to an even more difficult situation for those needing more energy. In light of the above, the following scenario is proposed below.

Hypothesis 3: Climate risk exhibits a moderating effect on the link between GF and EP.

3 Model construction and description of variables

3.1 Empirical framework

3.1.1 Basic model

We build a panel econometric model framework to study the link between GF and EP empirically. We consult the current literature and consider the effects of a number of control variables, such as economic growth, urbanization level, fiscal support, and industrial structure, among other aspects, to prevent endogeneity issues brought on by omitted variable bias. We converted all variables into natural logarithmic form to lessen the impact of any potential heteroskedasticity. To counteract the impact of variance size, the independent variables are normalized. Equation displays the model framework's precise form (1).

$$\text{LnEP}_{it} = \beta_0 + \beta_1 \text{LnGF}_{it} + \alpha \text{LnCtrls}_{it} + \varepsilon_{it} \quad (1)$$

where LnEP_{it} it stands for the EP level and is the explanatory variable, subscript i stands for the province, t stands for the year. In this study, the control variable is designated as LnCtrls_{it} . Our primary concerns are the estimated coefficient β_1 in the model's sign

direction and significance level. Based on the aforementioned theoretical presumptions, the projected coefficient β_1 is anticipated to be significantly negative.

According to the prior theoretical premise 3, when GF develops, energy output is impacted by climatic risk, which in turn influences EP. We incorporate the climate risk index as a moderating variable in Eq. (1) to test hypothesis 3, and we then use the cross-term coefficients of GF and climate risk index to confirm that climate risk modifies the relationship between GF and EP.

$$LnEP_{it} = \beta_0 + \beta_1 LnGF_{it} + \beta_2 LnCRI_{it} * LnGF_{it} + \alpha LnCtrls_{it} + \varepsilon_{it} \quad (2)$$

3.1.2 Method of moments quantile regression (MMQR)

Whether GF reduces EP and the moderating impact of climate risk index on them are investigated in Formulas (1) and (2). Nevertheless, we cannot determine how GF and climate risk function at various EP levels from these models. The diverse distribution of the full regression results is of more interest to policymakers and academics since it can suggest multiple development plans for nations and areas with various EP levels. In a linear model, the overall impact of the influencing factors on the dependent variable is estimated using the conventional ordinary least squares (OLS) method. The various consequences of the conditional distribution as a whole are not taken into account. Therefore, the genuine coefficients of the quantiles may be overestimated or underestimated in the related empirical results, which may even fail to define the relationship between variables appropriately. As a result, the MMQR model is used in this paper to examine how GF affects EP under various EP distributions.

Traditional regression models are further optimized by the MMQR model, which may retrieve all parameters using EP conditional distribution. Since the threshold is fixed to zero rather than being determined by data-driven processes, MMQR outperforms other nonlinear algorithms like "Nonlinear Autoregressive Distributed Lag (NARDL)," where nonlinearity is exogenously defined. It automatically resolves the endogeneity issue and thoroughly evaluates each of the model's fixed effects (Machado & Silva, 2019). As a result, experts claim that the MMQR strategy is the most appropriate method for handling heterogeneity and endogeneity since it is considered the best technology for managing heterogeneity and endogeneity and asymmetric and nonlinear relationships. MMQR can yield reliable estimates in several circumstances, even if the model is nonlinear. Moreover, this approach resists outliers, skewness, and heteroscedasticity (Koenker & Hallock, 2001). We propose the following formulas.

$$Y_{it} = a_i + X'_{it}\beta + P(\delta_i + Z'_{it}\gamma)U_{it} \quad (3)$$

where P denotes a probability, so $P\{\delta_i + Z'_{it} > 0\} = 1$. $(\alpha, \beta', \delta, r')'$ are estimated parameters. (α_i, δ_i) , $i = 1, \dots, n$, denotes the fixed effects of the individual i and Z is the selected components of the k -vector of the X having a transformable difference with the element 1. Z 's expressiveness is provided by:

$$Z_l = Z_l(X), l = 1, \dots, k \quad (4)$$

where Y_{it} is used to indicate the dependent variable (refer to EP in the paper). For any fixed person, X_{it} is an identical distribution over time (t). U_{it} is orthogonal to X_{it} and identically distributed among individuals (i) for time (t). The equation is rewritten as:

$$Q_\tau(Q|X_{it}) = (ai + \delta_i q(\tau)) + X'_{it}\beta + Z'_{it}\gamma q \quad (5)$$

where X'_{it} refer to control variable, includes PGDP, OPEN, GOV, UR and IND. X_{it} are independent variables (GF and CRI*GF), whereas $Q_{\tau}(Q|X_{it})$ designates the dependent variable (EP). The independent variables X_{it} 's structural quintiles are dependent on and situated in areas of EP.

3.2 Sample selection and data sources

This paper established a sample set of 30 provinces and autonomous regions in China from 2003 to 2020 (limited to available data, excluding Tibet, Hong Kong, Macao, and Taiwan). All relevant data were obtained from the WIND database.

3.3 Description of variables

Based on previous research, we developed a thorough evaluation system for GF and EP to investigate the association between GF and EP in various Chinese provinces. The indicators for GF and EP were initially chosen based on the following fundamental principles (Liu et al., 2018): (a) choosing widely cited indicators; (b) covering a wider range of subject matter related to GF and EP; and (c) relying on policies, opinions, and guidelines released by the government and provincial regions.

3.3.1 Explained variable: EP

We gauge the amount of EP in various Chinese provinces and areas using the EP index developed by Lee et al. (2022). This paper broadens the definition of EP to include a variety of factors, such as the types of energy sources that families use and how effectively energy is managed and consumed. To build the EP evaluation index system, we use 17 particular indicators in addition to four core indicators, including Residential Pollution and Affordability (RPA), Management Completeness (MC), Green and Clean (GC), and Service Availability (SA). We use the entropy weighting method to gauge the amount of provincial EP development in China. For specific indicators, see the paper of Lee et al. (2022).

To clearly identify the spatial distribution of energy poverty in China, this paper selected 2003, 2009, 2015, and 2020 to create distribution maps of China's energy poverty index (Fig. 2). Overall, there is a gradual alleviation of energy poverty. The eastern region, relatively economically developed with better infrastructure, experiences lower levels of energy poverty. Most areas in the east have good electricity supply and access to energy resources. The central and western regions are significant energy hotspots for poverty in China. These areas face numerous challenges in energy supply due to geographical conditions, economic backwardness, and relatively weak infrastructure. Remote mountainous areas, high plateaus, and desert zones may experience unstable electricity supply, inadequate grid coverage, and scarcity of energy resources.

3.3.2 Core explanatory variable: GF

The extent to which the local financial sector supports the clean industry in your area might be reflected in the level of GF development. The GF index system is frequently broken

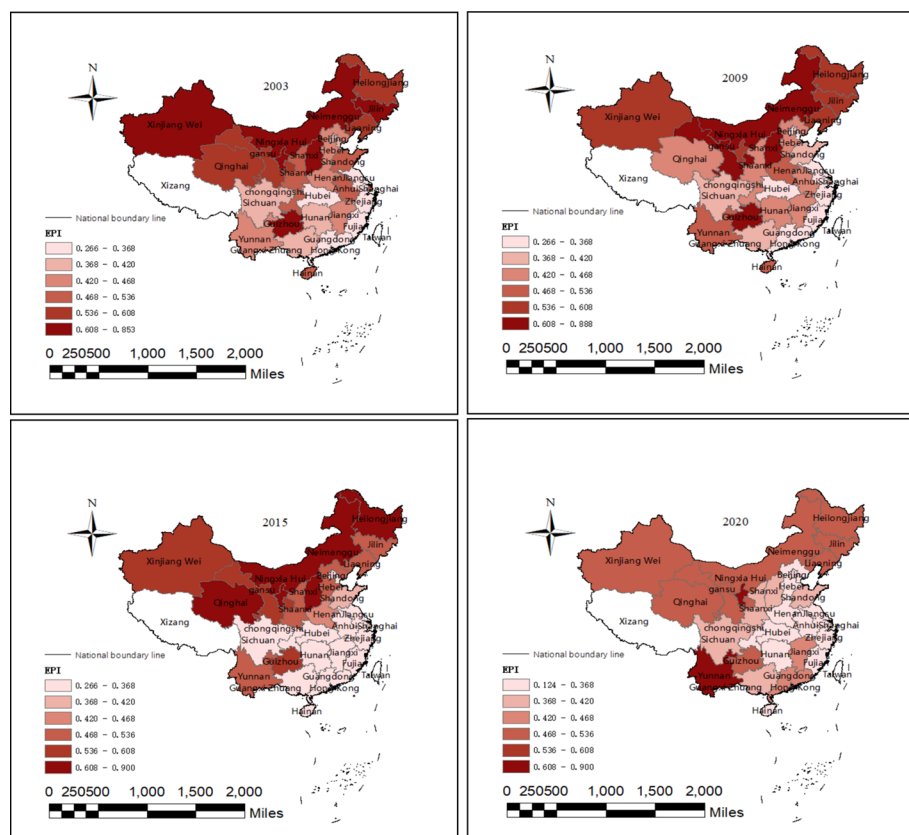


Fig. 2 Regional distribution mapping of energy poverty (EP)

down into five categories: carbon finance, green securities, green insurance, and green investments. The ratio of interest costs for highly energy-intensive industrial sectors to all industrial interest costs is a proxy for green credit among them. The percentage of environmental protection industry A shares' market value to all A shares' market value that is green securities. Green investment is represented by the ratio of regional environmental pollution control investment to provincial gross domestic product, and green insurance is represented by the income from agricultural insurance premiums to the value of agricultural output. The proportion of regional carbon dioxide emissions to regional GDP is a proxy for carbon finance. The GF index, which measures the degree of GF development in each location, is used in this paper to fit the five indicators mentioned above into it using the entropy approach. Table 1 displays the specific metrics.

The index system can be described as X_i ($i = 1, 2, \dots, N$), while the value of indicator X_i in period T can be expressed as X_{ijt} ($j = 1, 2, \dots, N$). This is assuming that the index system consists of K indicators, involves N evaluation objects, and spans M periods. For each indicator X_i , the value of Y_{ijt} is determined after standardization. Each indication has an information entropy (E_i) and a weight (W_i), respectively.

Table 1 Construction of the GF index indicators

Primary indicator	Secondary indicator	Tertiary indicator	Indicator definition	Indicator attribute
GF	Green credit	Proportion of interest paid by high-energy-consuming industries	Interest paid by high-energy-consuming industries/interest paid by industrial sector	–
	Green securities	Proportion of market value of high-energy-consuming industries	Market value of the top six high-energy-consuming A-shares/total market value of A-shares	–
	Green investment	Proportion of environmental pollution control investment	Investment in pollution control/GDP	+
	Green insurance	Proportion of agricultural insurance scale	Agricultural insurance income/total agricultural output value	+
	Carbon finance	Carbon intensity	Carbon dioxide emissions/GDP	–

$$Y_{ijt} = 100 \times \frac{X_{ijt} - \min(X_{ijt})}{\max X_{ijt} - \min(X_{ijt})} \quad (6)$$

$$Y_{ijt} = 100 - 100 \times \frac{X_{ijt} - \min(X_{ijt})}{\max X_{ijt} - \min(X_{ijt})} \quad (7)$$

$$E_i = -\ln(mn)^{-1} \sum_j \sum_t P_{ijt} \ln(P_{ijt}) \quad (8)$$

$$W_i = \frac{1 - E_i}{K - \sum_i E_i} \quad (9)$$

$$P_{ijt} = \frac{Y_{ijt}}{\sum_j \sum_t Y_{ijt}} \quad (10)$$

Figure 3 shows that when comparing the four distribution maps, China's overall green finance exhibited a significant upward trend from 2003 to 2020. Regions with higher levels of green finance in China are primarily concentrated in the eastern coastal and south-western areas. The East region is one of the most active and prosperous areas in terms of China's economic development, and it has also witnessed more mature growth of green finance. These regions possess developed financial systems and capital markets, attracting substantial green financial capital and investment. China's central and western areas need to catch up on economic development and slower infrastructure construction, resulting in a relatively weaker growth of green finance in these areas.

3.3.3 Moderating variable: climate risk index

In the mechanical analysis, we examine the relationship between GF and EP using the Climate Risk Index (CRI) as a moderating variable. China is experiencing escalating climate threats due to the changing global climate (Abbass et al., 2022). From 2020 to the summer of 2022, dozens of extreme climate events are concentrated in eastern China, such as a super-violent summer plum, the first empty typhoon in the Pacific Northwest in July, back-to-back droughts in autumn, winter, and spring, and extreme cold-warm winter transitions in 2020; a super-sandstorm in spring, heavy rainfall in Zhengzhou and snowstorms in northeast China in 2021; and record-breaking dragon boat floods and widespread extreme heat waves in 2022 (see Fig. 4). The Chinese government has also been putting effort into creating quantitative indicators to assess climate hazards brought on by extreme weather events. The China Climate Risk Index is based on six components: inundation, drought, typhoons, hot temperatures, low temperatures, and freezing. The National Climate Centre of China produces the index, and it is evaluated on a scale from low (0) to high (15). The risk associated with climate change increases with value. According to Fig. 2, the average value of China's climate risk index from 1991 to 2020 (6.4), compared to the average between 1961 and 1990, has increased by 58%. (4.3). China's climate risk index for 2020 is 10.8, the third-highest level seen since 1961.

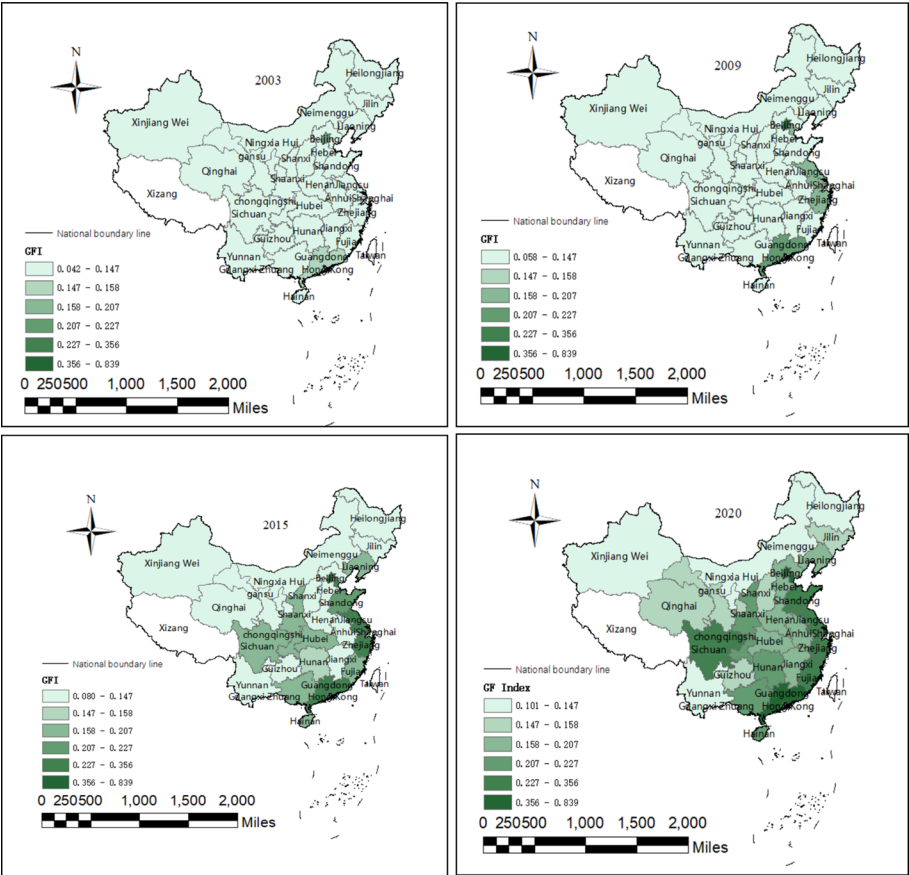


Fig. 3 Regional distribution mapping of green finance (GF)

Fig. 4 China’s climate risk index in 1970–2020

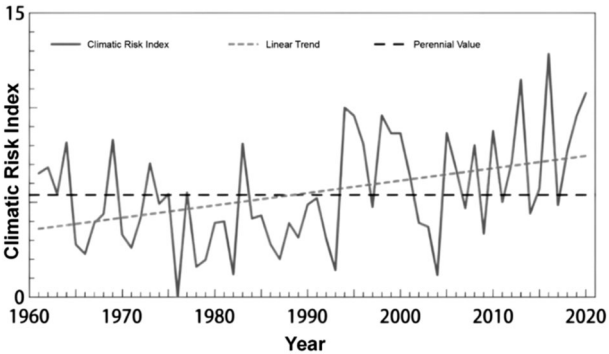


Table 2 Statistical description

Variable	Mean	SD	Min	Max	Skewness	Kurtosis
EP	0.470	0.140	0.150	0.860	0.480	2.640
CRI	1.970	0.900	0.260	4.560	0.280	1.930
GF	0.150	0.100	0.04	0.790	3.030	16.61
PGDP	3.920	2.740	0.360	16.42	1.340	5.170
OPEN	0.300	0.350	0.0100	1.880	2.180	7.630
RD	0.014	0.011	0.014	0.074	2.442	10.498
UR	0.530	0.150	0.260	0.900	0.690	3.180
IND	1.030	0.570	0.490	5.170	3.400	17.71

3.3.4 Control variables

We build on the research of Elliott et al. (2017) to account for pertinent factors and individual characteristics that may influence EP. We also incorporate a variety of control variables to increase the validity of our empirical findings. The level of economic development (PGDP) was chosen as one of the controls in this paper. Energy consumption structure is strongly influenced by economic development. (2) Degree of external receptivity (OPEN). The entry of cutting-edge foreign technology facilitates the transformation and modernization of industrial structures, and the expansion of trade openness impacts energy security and sustainable development. (3) Investment in research and development (RD). (4) Level of urbanization (UR). (5) Industrial structure (IND). Changes in the secondary industry will significantly impact energy consumption and the energy transition (Edomah, 2021; Gralla et al., 2017). Table 2 presents the results of descriptive statistics.

4 Empirical results and analysis

4.1 Baseline regression analysis

This work performs some preliminary checks before examining the effect of GF on EP. Table 3 displays the findings of the association between variables and the variance inflation factor (VIF). According to Table 3, the dependent variable has a negative correlation with the independent factors (GF and CRI) and the control variables. These variables' variance inflation factors are all less than 10, which rules out multicollinearity.

After testing the variables' stability, we study the overall impact of GF on EP through the standard OLS method, as shown in Eq. (1). In columns (1)–(4) of Table 4, we sequentially add climate risk and control variables to estimate the main effects of GF and climate risk, respectively. After controlling for city and year fixed effects, adding climate risk variables and time control variables yielded statistically significant results at the 1% level, supporting hypothesis 1 that GF has a significant negative impact on EP. GF can provide more environmentally friendly and economically affordable energy options for people who lack energy services through investment in clean energy, energy conservation, environmental protection industries, sustainable agriculture, and other areas (Wang et al., 2022a). For example, China's Jinzhai County has leveraged its abundant solar energy resources. In 2014, it initiated a pilot project to install photovoltaic power stations as poverty alleviation

Table 3 VIF test and correlation matrix

Variable	Vif	EP	CRI	GF	PGDP	OPEN	UR	RD	IND
CRI	1.040	− 0.127	1						
GF	9.650	− 0.563	0.093	1					
PGDP	8.020	− 0.491	0.140	0.833	1				
OPEN	2.180	− 0.409	− 0.006	0.352	0.345	1			
UR	7.550	− 0.426	0.104	0.732	0.842	0.604	1		
RD	4.090	− 0.506	0.115	0.825	0.676	0.416	0.738	1	
IND	3.040	− 0.300	0.012	0.763	0.547	0.124	0.528	0.635	1

Table 4 Basic regression results

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	No control variables	Add control variables		Add CRI*GF		
LnGF	− 0.258*** (− 4.83)	− 0.275*** (− 5.27)	− 0.198*** (− 3.25)	− 0.200*** (− 3.29)	− 0.271*** (− 5.17)	− 0.201*** (− 3.29)
LnCRI		0.014 − 1.24		0.013 − 1.12		
LnGFCRI					− 0.002 (− 0.46)	− 0.002 (− 0.32)
LnPGDP			− 0.162*** (− 2.76)	− 0.169*** (− 2.88)		− 0.167*** (− 2.83)
LnOPEN			− 0.075*** (− 3.81)	− 0.077*** (− 3.89)		− 0.076*** (− 3.85)
LnUR			0.476*** − 4.06	0.484*** − 4.14		0.482*** − 4.11
LnRD			0.004 − 0.13	− 0.002 (− 0.05)		0.001 − 0.04
LnIND			− 0.154*** (− 3.88)	− 0.153*** (− 3.86)		− 0.154*** (− 3.90)
Constant	− 1.378*** (− 9.83)	− 1.425*** (− 10.44)	− 0.938*** (− 4.92)	− 0.970*** (− 5.14)	− 1.412*** (− 10.31)	− 0.956*** (− 5.06)

t statistics are in parentheses

* $p < 0.1$

** $p < 0.05$

*** $p < 0.01$

facilities. Small-scale photovoltaic projects are installed in households by implementing a targeted poverty alleviation plan through distributed photovoltaic power generation. Impoverished families receive photovoltaic power station equipment for free or at a discounted rate, solving the problem of energy poverty while generating additional income through electricity.

In addition, GF can provide loans and investments to developing countries to assist them in developing RE and energy efficiency projects, alleviating EP issues (Wang & Zhao, 2022). As Mngumi et al. (2022) pointed out, the development of GF can also help improve the quality and reliability of energy infrastructure and services, thereby enhancing the sustainability and adaptability of energy services. This will help improve social and economic development and enhance social resilience and the ability to resist energy crises. However, in contrast, climate finance has a positive impact on EP. Natural disasters, extreme weather, and environmental changes caused by climate change (Streimikiene et al., 2020).

As shown in the equation, we propose the interaction term $GF \times CRI$ to examine whether and how climate risk influences the link between GF and EP (2). The projected findings are in columns (5) and (6) in Table 4. Although the regression coefficient of $GF \times CRI$ is considerably positive at the 1% level of statistical significance, the coefficient of GF is still negative, demonstrating that climate risk reduces the moderating influence of GF on EP. This data supports hypothesis 3 by showing that climate risk moderates the link between GF and EP. This finding confirms the research of Syed et al. (2023), who argue that the dynamic relationship between climate policy uncertainty and RE consumption has been overlooked. Climate policy uncertainty can significantly decrease RE consumption in both the long and short term. It is therefore recommended that climate policy uncertainty should be reduced to increase RE consumption.

The results are consistent with the idea that climate risk considerably impacts how GF and EP interact. This revelation requires careful examination due to its significance for developing RE technology and formulating sustainable energy policies. It suggests that governments and other relevant parties must consider the harmful effects of climate risk when boosting GF investments. Specific energy transition projects could need a lot of rare minerals and metals, like lithium, cobalt, and rare earths, to promote GF investments. Unfortunately, during harsh weather conditions, these rare metals and commodities are frequently in limited supply, which causes delays in the projected progress of green energy projects and impacts customers' energy supply. For example, in 2021, Yunnan Province, China, suffered from heavy rainfall and flooding, which severely affected tungsten mining in the region, leading to a shortage of rare metals and subsequently affecting the construction of green energy projects in the area. In promoting energy transition, some countries or regions may be affected by climate risks such as weather disasters or natural disasters, leading to a significant increase in energy transition costs. Also, extreme weather events in Texas, USA, in 2021 damaged solar and wind energy equipment, leading to a continuous rise in energy transition costs and affecting the energy consumption of low-income families and businesses. Climate risk may affect the effectiveness of GF investments through various channels, exacerbating EP. Therefore, when promoting GF investments, it is necessary to fully consider climate risk and take corresponding measures to mitigate it.

4.2 Empirical results of MMQR model

The empirical investigation presented above used linear regression techniques, although the effect of GF on EP might also be nonlinear. Figure 5 suggests that there may be a nonlinear relationship between them. To better research the nonlinear impact of GF on EP and consider the likelihood of significant individual effects and endogeneity difficulties across various locations, this paper used the MMQR method to examine this relationship among 30 Chinese provinces. This approach has the benefit of dealing with individual effects and

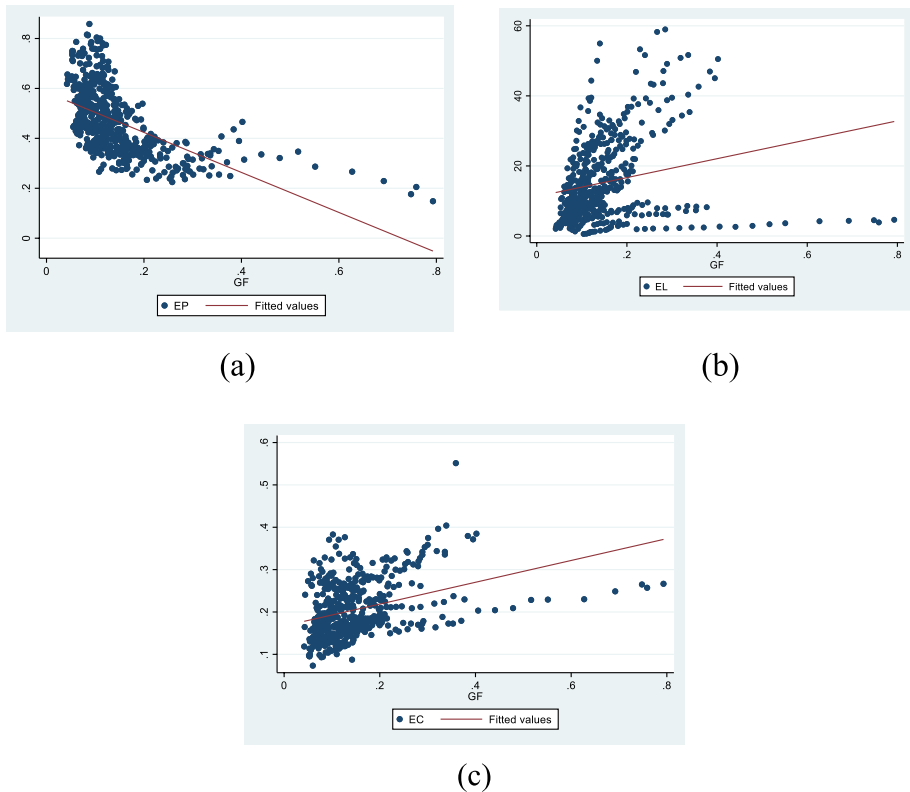


Fig. 5 **a** Scatterplot between EP and GF. **b** Scatterplot between EL and GF. **c** Scatterplot between EC and GF

endogeneity difficulties, enabling more thorough and reliable estimation. The findings are shown in Table 5.

The results show that the regression coefficient of GF is significantly negative at the 10th to 90th quantile levels. This indicates that the development of GF can alleviate EP, and there is a nonlinear relationship between the two, supporting Hypothesis 1. We also found that, unlike the baseline regression results, the coefficients at different quantile levels are significantly different, and the negative effect of GF on EP in the mid-to-low quantile regions (such as the eastern region) is most pronounced.

The findings indicate that, between the 10th and 90th quantile levels, the regression coefficient of GF is significantly harmful. This supports Hypothesis 1 since it shows that GF development can reduce EP and that there is a nonlinear link between the two. Also, we discovered that, in contrast to the findings of the baseline regression, the regression coefficients at various quantile levels change dramatically, with the mid-to-low quantile regions (such as the eastern region) showing the most substantial adverse effects of GF on EP. This indicates that GF is more sensitive when green investment increases in the east. However, the significance of the negative impact is relatively moderate at the medium-to-high quantile levels, indicating that its effect is diminished in the higher EP provinces (central and western regions). For example, in Jiangsu Province (a low-energy poverty

Table 5 Quantile estimation results of the basic model

Variables	Location	Scale	Quantiles				
			Q0.1	Q0.25	Q0.50	Q0.75	Q0.90
LnGF	− 0.373*** (− 8.00)	0.072*** (2.61)	− 0.488*** (− 8.37)	− 0.436*** (− 8.97)	− 0.376*** (− 8.07)	− 0.314*** (− 5.68)	− 0.256*** (− 3.63)
LnPGDP	− 0.083** (− 2.55)	− 0.037* (− 1.91)	− 0.024 (− 0.59)	− 0.05 (− 1.48)	− 0.081** (− 2.50)	− 0.113*** (− 2.93)	− 0.142*** (− 2.90)
LnOPEN	− 0.116*** (− 9.84)	− 0.001 (− 0.10)	− 0.115*** (− 7.80)	− 0.115*** (− 9.39)	− 0.116*** (− 9.88)	− 0.116*** (− 8.35)	− 0.117*** (− 6.61)
LnUR	0.582*** (6.73)	− 0.065 (− 1.26)	0.685*** (6.34)	0.639*** (7.08)	0.584*** (6.78)	0.529*** (5.16)	0.477*** (3.67)
LnRD	− 0.073*** (− 3.02)	0.002 (− 0.14)	− 0.076** (− 2.52)	− 0.075*** (− 2.96)	− 0.073*** (− 3.04)	− 0.071** (− 2.49)	− 0.070* (− 1.92)
LnIND	0.011 (0.36)	− 0.011 (− 0.59)	0.029 (0.73)	0.021 (0.63)	0.012 (0.37)	0.002 (0.06)	− 0.007 (− 0.14)
Constant	− 1.614*** (− 13.46)	0.309*** (4.34)	− 2.106*** (− 14.04)	− 1.886*** (− 15.04)	− 1.626*** (− 13.50)	− 1.362*** (− 9.54)	− 1.114*** (− 6.07)

t statistics are in parentheses

* $p < 0.1$

** $p < 0.05$

*** $p < 0.01$

region), the focus is on expanding energy conservation and environmental protection, clean energy, ecological environment, and other industries. In particular, the Bank of Suzhou supports clean energy, green buildings, and green infrastructure upgrading through green bond investments. While in Gansu Province (high energy poverty region), the bank focuses on supporting the development of the new energy industry, providing financing support for distributed photovoltaic, centralized photovoltaic, wind power projects, etc., to support the transformation of the energy structure in Gansu region. It means that in the different areas, the promotion of green finance is flexibly adjusted in combination with local resource endowment and industrial system.

These findings suggest that the eastern region has a reliable and effective GF system that offers services at fair prices, removes credit and informational restrictions, and increases the supply and effectiveness of RE. Our findings are in line with Zhao et al. (2023). The quantile regression results at various EP levels (corresponding to different provinces) clearly show the degree of its impact, which is helpful for policy-makers and governments to set targets and countermeasures for various levels of EP, even though the conclusions support the evidence that GF can reduce EP. Our findings align with those of Zhang et al. (2023) and Cheng and Taghizadeh-Hesary (2023). Zhang et al. (2023) suggest that the development of GF can effectively alleviate EP, whether in the short or long term. An increase in economic policy uncertainty leads to a decline in clean energy investment, hindering the EP reduction effects of GF. Cheng and Taghizadeh-Hesary (2023), using data from 20 Asian developing countries from 2010 to 2021, propose that for every 1% increase in the sustainable financing market, the EP gap in these Asian countries narrows by nearly 0.02%. Unlike Zhang et al. (2023), they categorize EP into different dimensions, finding that GF primarily focuses on improving

accessibility and cleanliness in the early stages and later shifts to efficiency improvement and completeness. In contrast, our study conducts heterogeneous analysis based on the severity of EP, highlighting that the higher the level of EP, the more pronounced the role of GF in those regions.

Moreover, control variables (UR, RD, and IND) virtually always have significant and advantageous effects on reducing EP. The marginal contributions of UR, RD, and IND are also more substantial in the eastern region (low quantiles), while they are smaller in the middle and western areas.

The demand for renewable energy rises annually as environmental protection becomes more widely understood. Renewable energy technologies may become less reliable and stable due to climate change, making their development and use more challenging. This increases the chance of an unstable energy supply, presenting new potential and difficulties for advancing renewable energy. We included the GF and CRI interaction factor into the MMQR model to investigate further the nonlinear influence of GF's development on EP under climate risk while considering the moderating role of climate risk under various quantile conditions.

Table 6 displays the MMQR regression findings. The results in the table show that the moderating effect of CRI on the relationship between GF and EP is considerably positive at the 25th and 50th percentiles, where the confidence level is 10%. This suggests that GF can encourage the growth and marketing of RE technology in the energy sector, easing EP. However, the relieving effect of GF is significantly diminished when there is a considerable degree of uncertainty surrounding climate change. This situation occurs more often

Table 6 Results of MMQR estimates considering climate risk

Variables	Location	Scale	Quantiles				
			Q0.10	Q0.25	Q0.50	Q0.75	Q0.90
LnGF	− 0.382*** (− 8.16)	0.067** (2.39)	− 0.488*** (− 8.43)	− 0.440*** (− 9.08)	− 0.386*** (− 8.26)	− 0.327*** (− 5.83)	− 0.273*** (− 3.79)
LnGF*CRI	0.013 (1.64)	− 0.002 (− 0.34)	0.016 (1.59)	0.015* (1.76)	0.013* (1.66)	0.012 (1.23)	0.01 (0.86)
LnPGDP	− 0.075** (− 2.31)	− 0.035* (− 1.81)	− 0.019 (− 0.48)	− 0.044 (− 1.31)	− 0.073** (− 2.25)	− 0.104*** (− 2.67)	− 0.133*** (− 2.66)
LnOPEN	− 0.115*** (− 9.83)	0 − 0.01	− 0.115*** (− 7.97)	− 0.115*** (− 9.52)	− 0.115*** (− 9.89)	− 0.115*** (− 8.22)	− 0.115*** (− 6.43)
LnUR	0.572*** (6.61)	− 0.061 (− 1.17)	0.668*** (6.25)	0.625*** (6.99)	0.575*** (6.69)	0.522*** (5.05)	0.472*** (3.57)
LnRD	− 0.071*** (− 2.95)	0.001 − 0.1	− 0.073** (− 2.47)	− 0.072*** (− 2.91)	− 0.071*** (− 2.97)	− 0.070** (− 2.42)	− 0.069* (− 1.86)
LnIND	0.009 (0.28)	− 0.008 (− 0.40)	0.021 (0.53)	0.016 (0.48)	0.009 (0.3)	0.003 (0.07)	− 0.003 (− 0.07)
Constant	− 1.624*** (− 13.55)	0.296*** (4.13)	− 2.094*** (− 14.11)	− 1.883*** (− 15.12)	− 1.641*** (− 13.65)	− 1.382*** (− 9.60)	− 1.140*** (− 6.13)

* $p < 0.1$

** $p < 0.05$

*** $p < 0.01$

in provinces with lower and medium EP. Due to the increased environmental risk caused by climate change, investing in GF requires higher costs to reduce environmental risk. This may increase the cost of GF and affect its role in alleviating EP (Zhao et al., 2023). For instance, the Bank of China has provided a subsidy of 85.62 million yuan to a wind power generation company in Zhejiang in the form of "renewable energy subsidy confirmation+pledge of electricity revenue rights." During the "13th Five-Year Plan" period, Zhejiang Province added 19.8 million kilowatts of installed power capacity, with a cumulative growth of 24.3%, mainly in the form of wind power, photovoltaics, and other renewable energy sources. However, in August 2019, after Typhoon "Lekima" made landfall, it caused damage to the power grids in more than ten areas, including Zhejiang, Fujian, Shanghai, and Jiangsu. Seventy-two substations with a voltage level of 35 kV and above and 4823 lines with a 10 kV and above were damaged or malfunctioning, leading to power outages for 7.72 million households. In September 2022, Typhoon "Mei Hua," which made landfall four times, had a destructive impact on the power grids of Zhejiang, Shanghai, Jiangsu, and Shandong.

4.3 Heterogeneity analysis

This paper separates the sample into the eastern, central, western, and northeastern areas according to their geographic positions to explore the regional disparities in the impact of GF on EP produced by regional variances. The results are displayed in Table 7. As observed, GF reduces EP in all regions but has a more significant effect in the central and western regions. The impact of GF on EP differs depending on the area. One explanation for this could be that the eastern part is more economically and technologically advanced, which makes it more advanced in using RE sources like wind and solar electricity, which are more commonly invested in and used. However, the adoption of renewable energy needs to catch up in the central, western, and northeastern regions due to economic and technological constraints. The marginal effect of GF in reducing EP is particularly noticeable in the west and central regions since EP is more severe in these areas due to their lower economic levels and relatively outdated energy infrastructure.

Moreover, in the 25th and 50th percentiles in western China, the moderating effect of climate risk on the connection between GF and EP is significant and favorable. This finding supports hypothesis 3 since it shows that climate risk exacerbates the detrimental effects of GF on EP. The central, eastern, and northeastern regions, however, did not have a significant impact from climate risk. Theoretically, this can be explained by the fact that Western China experiences more severe EP than other parts of the country. With GF support, western China's energy supply can be increased, and RE technology can be advanced, lowering EP. For instance, GF institutions can assist localized energy development, offering low-cost and dependable energy for low-income homes, such as solar photovoltaic power generation, small hydropower, etc. Furthermore, due to its geographic location and climatic circumstances, western China is more impacted by climate change, including drought, desertification, water shortages, and other problems. Because GF is typically used to promote environmental protection initiatives like renewable energy, energy efficiency, and emission reduction, these initiatives may encounter more technical and financial challenges in western China due to the region's harsh climate. In conclusion, GF in the West can support energy infrastructure development, technological advancement in the energy sector, renewable energy, energy conservation, and emission reduction initiatives. Still, it's crucial to assess the impact of climate risk carefully.

Table 7 The MMQR regression results for different regions

Dependent variable: EP						
	Variable	Q0.10	Q0.25	Q0.50	Q0.75	Q0.90
East	LnGF	− 0.388*** (− 3.56)	− 0.308*** (− 3.36)	− 0.202** (− 2.42)	− 0.087 (− 0.95)	0.002 (0.02)
	LnGFCRI	0 (− 0.01)	0.003 (0.15)	0.007 (0.4)	0.011 (0.6)	0.014 (0.65)
	Control	Yes	Yes	Yes	Yes	Yes
	N	170	170	170	170	170
Central	LnGF	− 0.515** (2.52)	− 0.500*** (2.75)	− 0.477*** (2.69)	− 0.450** (2.1)	− 0.425 (1.53)
	LnGFCRI	0.013 (− 0.68)	0.014 (− 0.79)	0.014 (− 0.84)	0.015 (− 0.72)	0.016 (− 0.58)
	Control	Yes	Yes	Yes	Yes	Yes
	N	102	102	102	102	102
West	LnGF	− 0.607*** (− 8.09)	− 0.613*** (− 10.16)	− 0.619*** (− 11.84)	− 0.627*** (− 10.73)	− 0.630*** (− 9.42)
	LnGFCRI	0.018 (1.41)	0.015** (2.46)	0.012** (2.3)	0.008 (0.78)	0.006 (0.51)
	Control	Yes	Yes	Yes	Yes	Yes
	N	187	187	187	187	187
North East	LnGF	− 0.462** (− 2.30)	− 0.507** (− 2.56)	− 0.544** (− 2.40)	− 0.639* (− 1.71)	− 0.761 (− 1.26)
	LnGFCRI	0.002 (0.15)	0.003 (0.34)	0.005 (0.43)	0.009 (0.46)	0.014 (0.45)
	Control	Yes	Yes	Yes	Yes	Yes
	N	51	51	51	51	51

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

4.4 Endogeneity test

This paper used the two-stage least squares (2SLS) technique to address endogeneity problems with the model variables. Endogenous variables are GF, climate risk, and the interaction term between GF and climate risk. To estimate the model, the lagged one-period values are used as instrumental variables. The GF and climate risk lagged values are predetermined and unaffected by current shocks. As a result, they are not linked with the error term, which helps somewhat alleviate the endogeneity issue. The columns (3)–(6) of Table 8 display the model estimation results. In line with earlier research findings, GF significantly reduces EP symptoms.

Table 8 the estimation results using FGLS and 2SLS respectively

Variables	FGLS			2SLS		
	(1)	(2)	(3)	(4)	(5)	(6)
LnGF	− 0.300*** (− 23.90)	− 0.362*** (− 16.48)	− 0.356*** (− 14.26)	− 0.257*** (− 13.98)	− 0.205*** (− 3.35)	− 0.203*** (− 3.29)
LnGF*CRI			0.005*** − 4.25			− 0.004 (− 0.67)
LnPGDP		− 0.014 (− 0.87)	− 0.050*** (− 2.77)		− 0.111*** (− 2.79)	− 0.113*** (− 2.82)
LnOPEN		− 0.041*** (− 5.32)	− 0.072*** (− 8.46)		− 0.066*** (− 3.49)	− 0.068*** (− 3.61)
LnUR		0.445*** − 7.94	0.478*** − 8.69		0.442*** − 3.9	0.446*** − 3.94
LnRD		− 0.062*** (− 5.00)	− 0.040*** (− 2.99)		− 0.016 (− 0.45)	− 0.021 (− 0.60)
LnIND		− 0.088*** (− 6.38)	− 0.077*** (− 5.11)		− 0.104*** (− 3.17)	− 0.102*** (− 3.11)
Constant	− 1.486*** (− 51.09)	− 1.660*** (− 27.32)	− 1.500*** (− 22.06)	− 1.332*** (− 26.96)	− 0.994*** (− 5.00)	− 1.014*** (− 5.14)

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

4.5 Robustness test

4.5.1 Variable replacement

To test the robustness of the estimation results, this paper replaces the dependent variable EP with electricity consumption structure (EC) and electricity production (EL), respectively, and the scatter plots of the relationship between EC and EL with GF are shown in Fig. 3b, c, respectively. As expected, there is a non-linear relationship between GF and EP. The robustness test results based on the MMQR method are shown in Table 9 and 10, respectively. After replacing the core dependent variable EP, GF is significantly positive at different quantile levels, indicating that GF can effectively improve electricity consumption structure and promote electricity production, thus alleviating EP. In addition, the moderation effect of climate risk is negative at individual quantile levels, indicating that climate uncertainty and risk harm the promotion of GF for electricity consumption structure and production.

4.5.2 Method replacement

The link between GF and the interaction between GF and climate risk has been re-estimated using the FGLS approach instead of the previous estimation method. The results of the parameter estimation are displayed in Table 8. The estimation results support the earlier

Table 9 Robustness checks: replacing core explanatory variables with EC

Variable	Location	Scale	Quantiles				
			Q0.10	Q0.25	Q0.50	Q0.75	Q0.90
LnGF	0.350*** (4.88)	− 0.079* (− 1.85)	0.470*** (5.9)	0.424*** (6.03)	0.363*** (5.17)	0.280*** (3.07)	0.216* (1.85)
LnGF*CRI	0.025** − 2.14	0.009 − 1.24	0.012 − 0.92	0.017 − 1.49	0.024** − 2.08	0.033** − 2.2	0.040** − 2.08
LnPGDP	0.247*** (5.11)	0.035 (1.23)	0.194*** (3.61)	0.214*** (4.54)	0.242*** (5.12)	0.278*** (4.53)	0.307*** (3.89)
LnOPEN	0.029 − 1.53	− 0.012 (− 1.08)	0.047** − 2.25	0.040** − 2.17	0.031* − 1.67	0.018 − 0.75	0.008 − 0.27
LnUR	− 0.672*** (− 5.35)	0.179** (2.41)	− 0.944*** (− 6.78)	− 0.839*** (− 6.82)	− 0.700*** (− 5.70)	− 0.513*** (− 3.20)	− 0.367* (− 1.79)
LnRD	− 0.101*** (− 3.30)	− 0.057*** (− 3.16)	− 0.014 (− 0.41)	− 0.048 (− 1.58)	− 0.092*** (− 3.06)	− 0.153*** (− 3.88)	− 0.200*** (− 3.99)
LnIND	− 0.067 (− 1.50)	− 0.044* (− 1.66)	0 (− 0.01)	− 0.026 (− 0.60)	− 0.06 (− 1.38)	− 0.106* (− 1.87)	− 0.141* (− 1.95)
Constant	− 2.018*** (− 11.32)	− 0.14 (− 1.33)	− 1.805*** (− 9.12)	− 1.887*** (− 10.82)	− 1.996*** (− 11.47)	− 2.143*** (− 9.45)	− 2.257*** (− 7.77)
Observations	510	510	510	510	510	510	510

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

findings, namely that GF can dramatically lower EP levels and that climate risk mitigates the adverse effects of GF on EP. Climate danger makes it difficult for GF to reduce EP.

5 Conclusion and implications

In order to determine if GF significantly reduces EP in 30 Chinese provinces, this paper uses the MMQR method. It also examines whether and how climate hazards impact the link between GF and EP. This research proposes a multivariate analysis methodology for connecting GF, CRI, and EP in balanced panel data by replacing and establishing instrumental variables to address robustness and endogeneity issues.

The major conclusions reached in this essay are as follows. First, GF significantly reduces EP symptoms. GF can offer finance and assistance for RE and energy efficiency initiatives, enhancing people's access to and utilization of energy. The MMQR data show that GF can reduce EP at all quantiles, however there are different levels of reduction. Second, the empirical models demonstrate that the negative correlation between GF and EP is significantly moderated by climatic hazards. Yet, only the 25th and 50th quantiles show a moderating effect that is meaningful. This indicates that when there is a large degree of uncertainty surrounding climate change, which is more typical in regions with low to medium EP, the relieving effect of GF is severely impacted. Finally, this moderating effect indicates spatial heterogeneity, mainly in western China.

Table 10 Robustness checks: replacing core explanatory variables with EL

Variable	Location	Scale	Quantiles				
			Q0.10	Q0.25	Q0.50	Q0.75	Q0.90
LnGF	− 0.035 (− 0.21)	0.319*** (3.3)	− 0.612** (− 2.28)	− 0.32 (− 1.54)	− 0.021 (− 0.13)	0.242 (1.4)	0.452** (2.29)
LnGFCRI	− 0.009 (− 0.39)	0.003 (0.21)	− 0.014 (− 0.38)	− 0.012 (− 0.41)	− 0.009 (− 0.39)	− 0.007 (− 0.28)	− 0.005 (− 0.18)
LnPGDP	1.474*** (12.93)	− 0.228*** (− 3.49)	1.886*** (10.4)	1.677*** (11.97)	1.464*** (12.77)	1.276*** (10.96)	1.126*** (8.44)
LnOPEN	0.092** (2.22)	− 0.044* (− 1.86)	0.172*** (2.61)	0.132*** (2.6)	0.091** (2.18)	0.054 (1.28)	0.025 (0.51)
LnUR	− 3.228*** (− 11.20)	0.868*** (5.26)	− 4.799*** (− 10.44)	− 4.003*** (− 11.19)	− 3.191*** (− 10.87)	− 2.475*** (− 8.34)	− 1.902*** (− 5.66)
LnRD	0.286*** (3.13)	− 0.257*** (− 4.89)	0.751*** (5.15)	0.516*** (4.55)	0.276*** (2.96)	0.064 (0.68)	− 0.105 (− 0.99)
LnIND	− 0.771*** (− 7.00)	− 0.005 (− 0.08)	− 0.761*** (− 4.35)	− 0.766*** (− 5.71)	− 0.771*** (− 7.04)	− 0.775*** (− 6.94)	− 0.779*** (− 6.02)
Constant	− 0.072 (− 0.18)	0.741*** (3.32)	− 1.412** (− 2.28)	− 0.733 (− 1.54)	− 0.04 (− 0.10)	0.571 (1.44)	1.059** (2.32)
Observations	510	510	510	510	510	510	510

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

First, GF significantly alleviates EP, indicating that higher levels of green finance development contribute to more significant support for energy conservation, emissions reduction, and green technology. To promote the comprehensive development of green finance, various stakeholders, including the government, financial institutions, businesses, and the public, need to take integrated measures. At the government level, it is essential to formulate comprehensive regulations and policies, establish incentive mechanisms, and strengthen regulatory oversight to ensure financial institutions adhere to green standards. Financial institutions can introduce green financial products such as green bonds and sustainable development loans, enhance ESG (Environmental, Social, and Governance) disclosure, and increase the development and promotion of green financial products. Businesses should devise sustainable development strategies, adopt clean energy, and actively participate in the green finance market. The public can contribute by increasing environmental awareness through education, choosing products that support green finance, and adopting low-carbon lifestyles.

Second, the natural, economic, and social conditions vary across different regions, making it necessary to formulate green finance development plans that align with local characteristics to support local sustainable development better. Considering that the alleviating effect of GF development is more pronounced in provinces with higher levels of EP, these provinces should increase investment in GF, introduce renewable energy technology infrastructure, enhance green technology levels, and improve energy production and utilization

efficiency. For instance, high-EP regions can establish dedicated GF funds, with contributions from the government, financial institutions, and businesses, to support renewable energy and environmental projects. Additionally, the government can encourage banks in the western regions through incentive policies to increase loans for green projects, providing support such as interest subsidies and risk-sharing. Moreover, collaborative efforts from relevant social entities, businesses, and the government can establish a specialized fund for research in the renewable energy industry, attract external investments as needed, stimulate regional economies, and encourage the transformation of research findings into productive forces.

Third, considering the developmental disparities among the eastern, central, and western regions of China, the government should tailor GF development policies to the specific conditions of each area. In supporting the transition from high-pollution, high-energy-consumption traditional industries to clean and low-carbon emerging industries through financial development, the development in the western and eastern regions should thoroughly consider the impact of climate risks. For instance, sandstorms and droughts in China's west could significantly affect the outcome of clean energy technologies such as solar and wind power. At the same time, typhoons and tsunamis could have severe consequences in some eastern provinces. Unquestioningly, increasing investments in clean energy technologies without considering these factors may exacerbate EP. Therefore, these regions should strategically plan traditional and renewable energy production structures, considering climate risks. They can leverage existing technological capabilities to adjust renewable energy production, optimize energy security systems, and alleviate EP.

Although the analysis in this paper provides valuable insights into EP in China, there are some limitations, which provide future research agendas and directions for experts and scholars to study further topics related to GF and EP. For example, the conditions of GF and EP can include multiple dimensions. An in-depth analysis of related issues may change the proxy variables, evaluation systems, and measurement methods for GF and EP. GF can also be studied separately according to different dimensions for EP alleviation. In addition, climate risks can be categorized into physical and transformational dangers in the future to explore further the heterogeneous roles of the two types of hazards.

Appendix A. Appendix

See Appendix Table 11.

Table 11 Nomenclature list

<i>Variables</i>	
GF	Green finance
EP	Energy poverty
CRI	Climate risk index
PGDP	Economic development
OPEN	Degree of external receptivity
RD	Investment in research and development
UR	Level of urbanization
IND	Industrial structure
RPA	Residential pollution and affordability
MC	Management completeness
GC	Green and clean
SA	Service availability
EC	Electricity consumption structure
EL	Electricity production
<i>Parameters</i>	
$\beta_0, \beta_1, \beta_2, \alpha, \beta', \delta, r'$	Estimated parameters
i	Stands for the province
t	Stands for the year
P	Probability
Z	Selected components of the k-vector
Y_{it}	Dependent variable
X_{it}	Independent variables
U_{it}	Orthogonal to X_{it}
X'_{it}	Control variable
$Q_{\tau}(Q X_{it})$	Dependent variable
E_i	Information entropy
W_i	Weight
2SLS	Two-stage least squares
<i>Acronym</i>	
WIND	Wind database
MMQR	Moment estimation quantile regression
IEA	International energy agency
RE	Renewable energy
COVID-19	Corona virus disease 2019
R&D	Research and development
OLS	Ordinary least squares
NARDL	Nonlinear autoregressive distributed lag
VIF	Variance inflation factor
ARDL	Autoregressive distributed lags

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Declarations

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