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More green digital finance with less energy poverty? The key role of climate risk

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ABSTRACT

The emerging field of green digital finance (GDF) holds promise for alleviating energy poverty (EP); however, its potential remains underexplored. Constructing a multidimensional index of GDF, this study investigates whether and how GDF development contributes to EP mitigation. Employing provincial-level panel data from China, our findings indicate that GDF development significantly reduces EP, and enhancing energy efficiency and deepening digitalization are potential mechanisms in this process. Moreover, climate risk demonstrates moderating/threshold effects, with an unfavorable role in addressing EP. Specifically, GDF exhibits a propensity to decrease EP at lower levels of climate risk, with the opposite effect observed at higher levels of risk. These findings offer essential guidance for policymakers to alleviate EP and promote sustainable development.

1. Introduction

Stable energy access is indispensable for contemporary economic growth, and despite continuous growth of global energy supply, inadequate energy access remains a significant impediment to development. As demonstrated by Ansu-Mensah and Kwakwa (2022), the inability to access energy results in a range of development challenges. This phenomenon has been termed energy poverty (EP), which manifests when a regional population encounters constraints in energy sufficiency, affordability, reliability, and security (Nussbaumer et al., 2012). EP entails barriers for individuals and businesses in obtaining adequate and affordable energy products and services, hindering their ability to meet energy needs. EP impedes sustainable economic growth and compromises physical health, consequently affecting social welfare (Apergis et al., 2022; Banerjee et al., 2021).

The recognition of EP as a pressing global concern has grown, notably with its inclusion as Goal 7 in the United Nations Sustainable Development Goals (SDGs), which stresses the imperative of "ensuring universal access to affordable and clean energy" (UNEP, 2021) and underscores the pivotal importance of eradicating EP in advancing sustainable development. The International Energy Agency defined EP in developing countries as the lack of access to clean energy sources such as electricity and natural gas, along with strong reliance on high-polluting traditional solid biomass energy for cooking. This definition resonates with the EP challenges faced in China, which is the world's foremost energy consumer (Dong et al., 2022; Li et al., 2023a). Despite achieving 100 % electrification in 2013 and eliminating absolute poverty in 2020 (Lin and Wang, 2020), China is still confronting significant EP issues, with over 30 % of households living in energy-poor conditions. Therefore, exploring potentially effective approaches to accelerate EP eradication in China is highly essential and urgent.

The continuous evolution of the financial sector has tremendous potential for alleviating EP. The United Nations Environment Program (UNEP, 2018) defined green digital finance (GDF) as the strategic application of digital finance or financial technology (fintech) to advance SDG attainment (Yue et al., 2022). Over the past few decades, GDF development has progressed globally through the use of internet technology to explore financial solutions that promote sustainable

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development (Walsh, 2021). By reducing transaction costs and mitigating information asymmetry, GDF has a crucial influence on supporting energy-efficient and environmentally friendly projects and improving energy supply, making it a pivotal instrument for fostering sustainable finance (IPSF—The International Platform on Sustainable Finance, 2020; Zhou et al., 2022).

China has actively pursued the advancement of GDF by implementing various measures such as establishing the Green Finance Information Management System (People's Bank of China, 2022), which provides a robust framework for managing green finance initiatives (Yu et al., 2022; Wang et al., 2022b; Wang et al., 2023). Ant Financial Services and the United Nations Environment Program (UNEP) collaboratively established the GDF Alliance, further highlighting China's commitment to integrating digital solutions into green finance. Moreover, the People's Bank of China has emphasized the country's determination to leverage digital technology to enhance green finance and bolster green financial risk management capabilities in the Financial Technology Development Plan (2022–2025). Although the concept and theoretical foundation of GDF are still evolving, its rapid development and positive impact on energy supply emphasizes its potential to tackle the complexities of EP in the China.

Despite the limited amount of relevant research regarding the GDF–EP nexus, the rationale behind investigating this relationship has been the inherent connection between financial development and energy expansion. Most green energy projects are particularly financially constrained due to inherently high uncertainty concerning investment and extended payback periods (Gabriel et al., 2016). A variety of research has demonstrated that digital finance and fintech have made green financial systems more accessible, improving energy efficiency and contributing to sustainable energy development. Wu and Huang (2022) concluded that digital finance offers new opportunities for sustainable development by improving new energy enterprises' financial performance and promoting the benefits.

Cao et al. (2021) determined that digital finance promotes energy/environmental performance in China by financing green innovation. Conversely, GDF also has strong potential for expanding financial services to serve those experiencing EP and contributing to the fulfillment of SDG 7. Previous research has examined how financial access and households' energy affordability affect EP (Cheng et al., 2023; Dogan et al., 2021; Dong et al., 2022). Yu et al. (2022) demonstrated that digitalization could expand financial inclusion, making renewable energy more affordable for low-income households. In addition, GDF increases individuals' motivation and capability to purchase clean fuels (Dong et al., 2022; Gomber et al., 2018; Li et al., 2023b). In summary, GDF facilitates clean energy expansion and transformation, potentially impacting EP. Nevertheless, to the best of our knowledge, no systematic study has examined the GDF–EP nexus.

To fill the gap in the literature, this study investigates GDF's impact on EP across 30 provinces in China from 2011 to 2020. We first construct a compound GDF index that integrates five subindices for green finance and digital finance. Second, we investigate GDF's impact on EP and further explore regional heterogeneity in terms of socioeconomic conditions. Third, this study examines the mediating mechanisms through which GDF lowers EP considering energy efficiency and digitalization level. Moreover, given the significant influence of climate extremes on energy activities (Chen et al., 2022), we examine the moderating/threshold effects of climate risk.

The resulting empirical evidence indicates that GDF has a marked influence on mitigating EP. While GDF promotes EP in China's eastern and central areas, no significant inhibitory effect is found for the west region. We further investigate heterogeneity in terms of socioeconomic conditions, finding that high-level economic growth, financial development, and technological progress are prerequisites for optimizing the beneficial role of GDF in addressing EP. Furthermore, climate risk indirectly hampers the EP alleviation process. Results from the threshold model indicate that GDF could have an inhibitory effect on EP when climate risk is within its certain threshold. Overall, this study demonstrates that GDF mitigates EP in China by enhancing energy efficiency and promoting digitalization, while also highlighting the critical moderating/threshold effects of climate risk.

This study makes the following marginal contributions. First, we introduce a novel and comprehensive indicator system to evaluate China's GDF. This multidimensional index provides a nuanced understanding of the synergy and deep integration between digital instruments, fintech, green finance, and sustainable finance in China, capturing the evolving dynamics of GDF development. Second, we verify that GDF development significantly reduces EP and analyze the potential mechanisms of digitalization and energy efficiency. The findings highlight the potential of GDF as a transformative force for addressing EP, complementing the existing literature on inclusive finance (Dong et al., 2022) and financial market participation (Cheng et al., 2023) as determinants of EP. Third, our study makes a key contribution by assessing the moderating role of climate risk in the GDF–EP nexus, demonstrating that GDF's effectiveness diminishes in regions experiencing high climate risk. These results underscore the significance of incorporating climate risk in future policy designs. Fourth, we consider regional heterogeneity, offering strategically tailored policy recommendations to alleviate regional EP.

The remainder of this study proceeds as follows. The next section reviews the pertinent studies in the literature and introduces three primary hypotheses to be examined. Section 3 outlines the approaches and methodology employed. In Section 4, we discuss the data sources and how the variables are constructed. Section 5 presents the empirical findings. Along with relevant policy recommendations, Section 6 provides a brief conclusion.

2. Hypotheses development, and theoretical framework

The escalating prevalence of EP has sparked significant concern among academics and policymakers, given its profound impact on hindering sustainable socioeconomic development (Banerjee et al., 2021; Oum, 2019; Sharma et al., 2019; Scarpellini et al., 2019; Wang et al., 2015). In response to these concerns, previous investigations have extensively assessed the determinants of EP. The catalysts highlighted therein have primarily revolved around technological innovation, education, cultural factors, renewable energy, and globalization (Apergis et al., 2022; Chaudhry and Shafiullah, 2021; Lee et al., 2022).

There remains a paucity of research addressing the significance of GDF in influencing energy poverty. The economic intuition behind the GDF-EP nexus could potentially be traced to recent related literature. First, financial development plays a significant role in shaping both energy and environmental outcomes (Khan et al., 2021). In many developing nations, credit constraints hinder environmental improvements, emphasizing the importance of green finance policies (Tian and Lin, 2019). On the other hand, energy access is closely correlated with improved services of financial institutions, particularly in developing countries. Financial inclusion has been identified as a critical factor in reducing EP by providing access to financial services that enable households to transition to cleaner energy sources. Koomson and Danquah (2021) demonstrated that inclusive finance has reduced fuel shortages in Türkiye and Ghana, and Dong et al. (2022) confirmed that financial inclusion promotes access to clean fuel in China. Cheng et al. (2023) further extended these findings by highlighting the role of household financial participation in alleviating EP. Therefore, financial inclusion is a crucial channel for enabling energy access, particularly in low-income, high-unemployment contexts (Koomson and Danquah, 2021).

Second, a close connection exists between green finance, digital finance, and renewable energy development. Although accelerating the growth of the renewable energy industries and innovating new energy technologies are effective strategies for eradicating EP, renewable energy projects are considered risky and expensive to finance due to high initial costs, extended payback periods, and inherent uncertainties in technological innovation (Gabriel et al., 2016). Green finance, which integrates environmental sustainability into financial provisions, can help renewable energy projects overcome such financing constraints. For example, using a cross-country sample of 44 nations from 2007 to 2020, Alharbi et al. (2023) demonstrated that green finance, particularly through green bonds, significantly fosters renewable energy production. Moreover, studies have indicated that digital finance makes green financial systems more accessible and strengthens the influence of green finance (Zhou et al., 2023). Cao et al. (2021) found that digital finance improves China's energy/environmental performance by lowering entry barriers to financial services and reducing information asymmetry in financing renewable energy projects. Based on the discussion above, we propose the first hypothesis.

Hypothesis 1. GDF development alleviates EP.

The link between financial development and EP has been explored through multiple lenses, including income, energy efficiency, and energy prices (Moore, 2012; Nguyen and Nasir, 2021). In the context of GDF, enhancing energy efficiency is also a crucial impact mechanism. Green finance is conducive to reshaping China's coal-dominant energy consumption structure, which improves energy efficiency (Lee et al., 2023). Green finance, which is distinguished by the amplification of green functions within the financial system, facilitates investments in renewable energy technologies (Acemoglu et al., 2016; Madaleno et al., 2022). Renewable energy development contributes to improving energy efficiency, subsequently alleviating EP (Dong et al., 2021a, 2021b). Furthermore, digital finance facilitates industrial structure upgrading and encourages enterprises to engage in energy-efficient production, ultimately improving energy efficiency (Ahmad and Wu, 2022; Baloch et al., 2021). Digital finance is also instrumental in improving the quantity and quality of green technical innovation (Cao et al., 2021; Lin et al., 2023). The accelerated expansion of digital finance complements green finance development, resulting in a synergistic form of financial development that systematically decreases energy intensity and enhances energy efficiency.

Digitalization is another key mechanism by which GDF addresses EP. By leveraging fintech, GDF enables broader access to financial services, allowing individuals to obtain online loans, payments, and insurance, which drives the digitalization of economic activities (Chen et al., 2023). Increased digitalization is a pivotal driver for the achieving the SDGs, fostering economic expansion and advancing poverty alleviation and energy access (Liu et al., 2022; Wang et al., 2022a). Razzaq et al. (2023) asserted that digitalization has the potential to diminish credit barriers, providing businesses with cost-effective financing solutions that establish the foundation for green development projects. Consequently, digitalization has the promise of assisting the economy in overcoming energy challenges and alleviating EP (Wu and Huang, 2022). Moreover, GDF can promote energy systems' digitalization through technologies such as smart grids, the Internet of Things, and big data analytics, which can directly optimize the allocation and use of energy (Liu et al., 2022). Building upon the above dialogues, we posit our second hypothesis.

Hypothesis 2. GDF reduces EP by improving energy efficiency and accelerating digitalization.

Grossman and Krueger's (1995) environmental Kuznets curve (EKC) hypothesis, which posits an inverted U-shaped correlation between economic activity and environmental quality, has become a key theoretical foundation in environmental economics. According to this hypothesis, economic growth initially leads to environmental degradation, but beyond a certain income threshold, further growth improves environmental outcomes. As the evolving complexity of the global economy, the threshold effect is influenced not just by a nation's GDP growth, but also by its economic stability, financial conditions, and climate-related risks. In the spirit of this framework, recent research has examined how climate risk affects energy activities and the environment, given its significant influence on socio-economic factors.

When analyzing the relationship between GDF and EP, climate risk is a crucial consideration. Since clean energy is highly climate-sensitive, expanded climate risk has become a major obstacle to energy development. Recurrent climate crises (i.e., floods and droughts) exacerbate EP by reducing energy production efficiency (Duan and Wang, 2018; Lee et al., 2023; Wang et al., 2018). Such events can damage critical energy infrastructure, further limiting energy access, particularly for vulnerable populations. Lee et al. (2022) demonstrated that climate risks constrain the integration of renewable energy and energy efficiency improvement. As climate risk intensifies, the ability of GDF to support energy access may be diminished. In addition, extreme weather events can damage digital infrastructure such as data centers, telecommunications networks, and power supply systems (Sadeghi Khomami et al., 2019), and this damage can impede the digitalization process, weakening the effectiveness of GDF in alleviating EP.

More importantly, climate risk can directly shock financial systems. Climate-related risks such as extreme weather events and long-term environmental changes introduce significant uncertainty. Financial institutions and investors may be more cautious due to higher risks and uncertainties, resulting in withdrawal from financing green projects (Campiglio et al., 2023). Climate change also increases the risks of providing services to low-income populations, which slows the progress of inclusive finance (Borgi et al., 2023). As noted by Monasterolo (2020), unanticipated climate-related physical and transition shocks can have long-term effects on a country's financial health and undermine the function of the financial system. This highlights the nonlinear nature of GDF's impact, as its effectiveness in alleviating EP diminishes under higher levels of climate risk. This nonlinear dynamic resonates with the broader scholarly discourse on the detrimental impact of climate risk on energy development progress (Wei et al., 2023; Corner et al., 2011). Considering the growing attention to climate risk and its implications for energy development, we propose the following hypothesis:

Hypothesis 3. Climate risk moderates the relationship between GDF and EP.

Based on the hypotheses developed above, we summarize the theoretical research framework of this study in Fig. 1.

3. Methodology

Drawing from the prevalent standard in other studies concerning EP (Dong et al., 2021a, 2021b; Lee et al., 2022), we set up the benchmark regression model as:

$$EP_{it} = \beta_0 + \beta_1 GDF_{it} + \gamma Controls_{it} + \delta_i + \varphi_t + \varepsilon_{it}. \tag{1}$$

Here, $i = 1, \ldots, N$ refers to the cross-sectional units covering China's 30 provinces, whereas $t = 1, \ldots, T$ indicates the time period. The dependent variable signifies energy poverty level (*EP*). Green digital finance (*GDF*) represents a primary explanatory variable of interest. $Controls_{it}$ covers various variables influencing energy poverty, including GDP per capita (*PGDP*), financial support (*FS*), foreign direct investment (*FDI*), R&D spending (*RD*), and quality of education (*EDU*). Finally, δ_i represents province fixed effects, φ_t denotes time fixed effects, and ε_{it} stands for the error term.

To explore the mechanism through which green digital finance influences energy poverty, we construct the following model:

$$Mediator_{it} = \beta_0 + \beta_1 GDF_{it} + \gamma Controls_{it} + \delta_i + \varphi_t + \varepsilon_{it}, \tag{2}$$

$$EP_{it} = \beta_0 + \beta_1 GDF_{it} + \lambda Mediator_{it} + \gamma Controls_{it} + \delta_i + \varphi_t + \varepsilon_{it}. \tag{3}$$

Here, $Mediator_{it}$ encompasses mediator variables such as energy intensity (*EI*) and digitalization (*DIF*). Furthermore, to examine the potential moderating effect of climate risk, we introduce an interaction term for climate risk index (*CRI*) and green digital finance (Lee et al., 2023). The model is shown below.

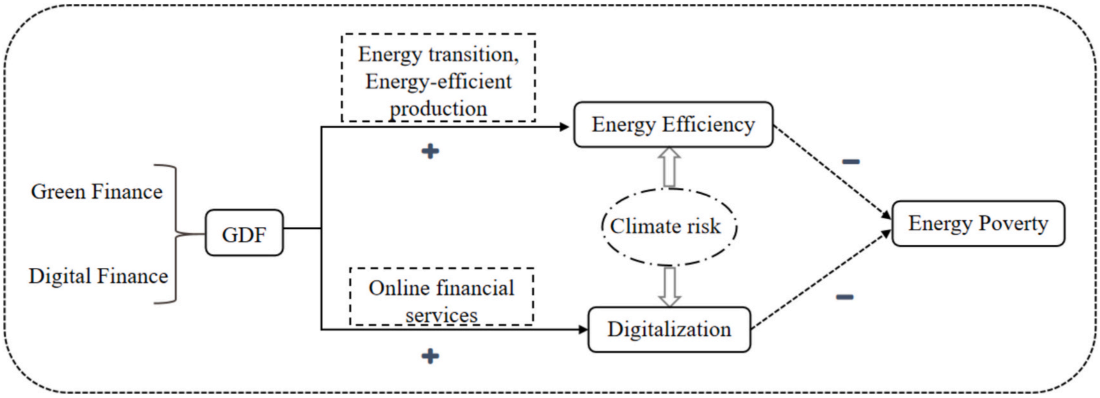

Fig. 1. Theoretical framework.

$$EP_{it} = \beta_0 + \beta_1 GDF_{it} + \beta_2 GDF_{it} \times CRI_{it} + \gamma Controls_{it} + \delta_i + \varphi_t + \varepsilon_{it}. \tag{4}$$

We finally examine whether climate risk introduces a non-linear relationship between GDF and energy poverty. The dynamic panel threshold (DPT) model is applied, as it addresses potential endogeneity issues by utilizing the generalized method of moments (GMM) estimation. Additionally, the DPT model allows for endogeneity of the threshold variable, thereby enhancing the effectiveness of estimation. The model specification is as follows:

$$EP_{it} = \beta_0 + \beta_1 EP_{it-1} + GDF_{it}^{'}\beta + \left(1, GDF_{it}^{'}\right)\delta 1\{CRI_{it} > \gamma\} + Controls_{it}^{'}\omega + \left(1, Controls_{it}^{'}\right)\delta 1\{CRI_{it} > \gamma\} + \mu_i + \varepsilon_{it} \tag{5}$$

4. Data description

4.1. Methods of sampling and sources of data

This study assesses GDF's influence on energy poverty, utilizing a balanced panel dataset covering 30 provinces in China from 2011 to 2020. Table A1 provides definitions and descriptive statistics, with data collected from various sources including China's provincial statistical yearbooks, China's energy statistical yearbook, China's statistical yearbook of the environment, and the Wind database. Table A2 reports cross-correlations of all the variables.

4.2. Dependent variable: Energy poverty

Building on the energy development index frameworks proposed by Pachauri et al. (2004) and Lee et al. (2022), we concentrate on four primary dimensions of energy poverty: residential pollution and affordability, human capital, green cleaning, and service availability. The comprehensive framework integrates a wide range of indicators encompassing pollution, affordability, human capital, environmental sustainability, and service availability. Therefore, this multi-dimensional index system enables a nuanced assessment of energy poverty, accounting for regional variations in economic conditions. To ensure robustness of our analysis, we investigate two additional supplementary indicators - electricity production (EL) and the structure of renewable energy consumption (EC) - as alternative metrics for assessing energy poverty. EL quantifies the percentage of electricity in GDP (measured in units of 100 million yuan per 100 million kWh), while EC denotes the proportion of electricity consumption to total energy consumption (Lin and Zhu, 2020).

4.3. Core explanatory variable: Green digital finance

Green digital finance has emerged as a rapidly developing form of finance over the past decade and generally refers to leveraging emerging Internet technology to provide financial solutions that promote sustainable development. In this study we construct a measure of GDF by integrating the specific use of both green finance and digital finance components. The measurement relies on the transaction volume and cash flow of green finance and digital finance. In view of green finance, we draw upon research by Flammer (2019), focusing on five sub-indices related to green-oriented investment, insurance, credit, government support, and security. Similarly, in view of digital finance and inspired by the works of Li et al. (2023b), Wu and Huang (2022), and Yu et al. (2022), we consider five sub-indices related to digital-oriented credit, insurance, investment, monetary fund availability, and payment services. Table A3 lists the measurement and characteristics of these sub-indices.

This study uses the entropy weight method to assign weights of the subindices, following the steps outlined below. First, we standardize the data as follows:

$$Z_h(it) = \begin{cases} \dfrac{X_h(it) - min[X_h(it)]}{max[X_h(it)] - min[X_h(it)]}, if\ X_h(it)\ is\ a\ positive\ subindex \\ \dfrac{max[X_h(it)] - X_h(it)}{max[X_h(it)] - min[X_h(it)]}, if\ X_h(it)\ is\ a\ negative\ subindex \end{cases}. \tag{6}$$

where $X_h(it)$ represents a subindex of green finance or digital finance, with the method of making the subindex dimensionless dependent on its characteristics. $Z_h(it)$ denotes the standardized $X_h(it)$. We then calculate the weight of the subindex as follows:

$$P_h(it) = \frac{Z_h(it)}{\sum_{i=1}^{N}\sum_{t=1}^{T} Z_h(it)}\ (i = 1, \dots, N; t = 1, \dots, T). \tag{7}$$

$$E_h = -ln(N^*T)^{-1}\sum_{i=1}^{N}\sum_{t=1}^{T} P_h(it) lnP_h(it). \tag{8}$$

$$W_h = \frac{1 - E_h}{\sum_{h=1}^{H}(1 - E_h)} (h = 1, \dots, H). \tag{9}$$

where $P_h(it)$ represents the proportion of standardized subindex h of province i in year t to the total, E_h denotes the information entropy associated with the standardized subindex h, and W_h signifies the weight assigned to the standardized subindex h.

We then construct the final index as follows:

$$C(it) = \sum_{h=1}^{H} Z_h(it) W_h. \tag{10}$$

where $C(it)$ is the comprehensive index of green finance or digital finance. Thereafter, we combine the green finance and digital finance indices into the GDF index according to the method above.

4.4. Moderating/threshold variable: Climate risk index

The climate risk index (CRI) is sourced from China's National Climate Center and functions as a quantitative metric to assess climate risks stemming from adverse weather phenomena. Developed by the government, the index consolidates data from five key components: waterlogging, typhoon, drought, freezing, and extreme high temperature, with values ranging from 0 to 10. A greater index value denotes an elevated level of climate risk. It is noteworthy that the climate risk index encompasses seasonal variations in its overall magnitude and the primary drivers behind these fluctuations.

4.5. Control variables

Drawing from the literature, we incorporate several control variables to capture additional factors influencing EP. Economic development level is represented by the logarithmic value of GDP per capita (PGDP), while financial support level is indicated by the ratio of financial institutions' loan balances to GDP (FS). These metrics are selected based on studies conducted by Ren et al. (2022). In addition, we utilize foreign direct investment per capita and the number of R&D personnel to gauge foreign direct investment (FDI) and local firms' innovation efforts (RD), respectively. Finally, average years of education are integrated as a proxy for education level (EDU), aligning with the findings of Apergis et al. (2022) that emphasize the role of education in influencing energy poverty.

4.6. Preliminary data tests

Prior to commencing the regression analysis, we conduct stationarity tests on the panel data to prevent spurious regression. The LLC and Fisher-ADF unit root tests are utilized to assess whether the variables of interest display unit roots. The outcomes of Table A4 demonstrate that all variables are stationary in levels, thereby rejecting the null hypothesis of unit roots.[1]

5. Empirical results

5.1. Influence of GDF on EP

We initially use the fixed effects model to evaluate GDF's impact on EP, as shown in Table 1. Columns (1)–(3) only control for fixed effects, and Columns (4)–(6) introduce additional control variables. The findings in Column (1) indicate that the coefficient of GDF is significantly negative at the 1 % level. We next focus on the subcomponents of green finance (GF) and digital finance (DF). The results in Columns (2) and (3) reveal significantly negative coefficients for GF and DF, which align with our baseline conclusions. When we introduce relevant control variables in Columns (4)–(6), the estimated results generally maintain the signs and significance. Overall, these empirical findings demonstrate that GDF development tends to alleviate regional EP, supporting Hypothesis 1. This indicates that the Chinese government should further promote GDF to support more households under energy-poor condition.

Our findings align with Yu et al. (2022), who emphasized that promoting GDF facilitates renewable energy growth, improving clean energy access and consumption. In essence, GDF leverages digital tools to fulfill the demand for GF, effectively bridging the GF gap. Chen et al. (2021) determined that integrating technologies like big data into the green energy sector enhance energy efficiency, improve energy security, and advance sustainable development. In this context, GDF's influence on EP mirrors traditional finance channels, encompassing effects such as capital support, resource allocation, and technological innovation, albeit with intensified greening and fintech features. By catalyzing innovation in renewable energy technology and addressing the financing needs for green energy infrastructure and projects, GDF has a pivotal role in improving energy use and addressing EP.

5.2. Regional differences

Significant regional development disparities in China are attributable to variations in geographical location, resource distribution, and socioeconomic factors, and may also manifest in GDF's impact on EP. To explore these geographical variations, we classify our sample into eastern & central (E&C), and western (West) geographic groupings, presenting the estimation results for these groups in Table 2.

The results indicate that GDF development notably alleviates EP in China's eastern and central areas, which aligns with Zhou et al. (2022), who found that impact of DF on green growth is more prominent in eastern China than the western region. The eastern region's environment, featuring rapid economic development and an advanced financial system, has facilitated the rapid transformation of fintech and sustainable finance innovations into drivers for EP alleviation. Conversely, the western region faces challenges such as inadequate incentives, low innovation efficiency, and prolonged fintech innovation cycles, resulting in less significant GDF promotional effects on energy development and sustainable growth (Liu et al., 2022; Lee et al., 2023). These findings highlight the importance of establishing a supportive economic environment to maximize the benefits of GDF. Policymakers in regions with weaker financial infrastructure (i.e., the western region) can draw from these insights to develop strategically targeted interventions to bolster local economies' absorptive capacities and improve the economic returns on GDF investments.

5.3. Heterogeneity of different economic, financial, and technical conditions

The regional disparities in GDF's impact on EP are related to nuanced economic development across China's diverse regions. To comprehensively analyze these variations in economic and financial development, we categorize the sample into low and high economic growth (LGDP and HGDP), low and high financial support (LFS and HFS), and low and high technological progress (LRD and HRD), as presented in Table 3.

Our findings reveal that GDF development exerts a significantly negative influence on EP in provinces with higher economic growth, financial support, and technological progress. The rationale for this observation may be explained by absorptive capacity, which signifies a region's readiness and capability to effectively use GDF for sustainable growth. Studies have highlighted the crucial significance of absorptive capacity in leveraging financial resources for sustainable development (Du et al., 2019; Lee and Lee, 2022; Qi et al., 2022; Yu et al., 2022). Moreover, regions with favorable economic and technological conditions are better equipped to allocate and use productive factors in economically efficient and energy-saving ways. These areas often have the material resources and technological infrastructure that are required to enhance energy production methods, promote energy efficiency, and improve energy structures, ultimately contributing to EP alleviation. This emphasizes the role of economic growth as a driver of the effective GDF. As economies expand, they generate additional financial and technical resources to support renewable energy projects, resulting in superior energy security and poverty reduction. Conversely, the diminished economic impact of GDF in low-growth regions highlights the need for more robust policy frameworks to facilitate energy transitions.

[1] To assess the robustness of the findings against potential cross-dependence, we also applied Bai and Ng (2004)'s PANIC test and Pesaran (2007)'s cross-sectionally augmented IPS (CIPS) test. The results confirmed that our primary conclusions remain unchanged.

Table 1
Benchmark regression model.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
GDF	−0.107***			−0.364**		
	(−3.089)			(−2.322)		
GF		−0.274***			−0.299***	
		(−3.183)			(−3.143)	
DF			−0.045***			0.028
			(−2.799)			(0.125)
PGDP				−0.378***	−0.364***	−0.309**
				(−3.026)	(−3.047)	(−2.374)
FS				−0.084**	−0.089**	−0.046
				(−2.019)	(−2.256)	(−0.925)
FDI				−0.008	−0.008	−0.015
				(−0.858)	(−0.891)	(−1.479)
RD				0.193***	0.189***	0.186***
				(7.380)	(7.365)	(7.071)
EDU				−0.371	−0.348	−0.401*
				(−1.510)	(−1.409)	(−1.656)
Province	NO	NO	NO	Yes	Yes	Yes
Year	NO	NO	NO	Yes	Yes	Yes
Adj R^2	0.857	0.857	0.855	0.886	0.888	0.883
F-statistics	9.542***	10.133***	7.837***	13.559***	14.960***	13.745***
Observations	270	270	270	270	270	270

Notes: t-statistics are in brackets. $^*p < 0.1$,$^{**}p < 0.05$,$^{***}p < 0.01$.

Table 2
Distinctions between regions.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	E&C	West	E&C	West	E&C	West
GDF	−0.364***	−0.164				
	(−2.728)	(−0.257)				
GF			−0.299***	−0.200		
			(−3.448)	(−0.441)		
DF					0.170	0.219
					(0.874)	(0.515)
PGDP	−0.182	−1.122***	−0.200	−1.128***	−0.106	−1.154***
	(−1.119)	(−3.152)	(−1.235)	(−3.110)	(−0.649)	(−3.424)
FS	−0.087*	−0.169**	−0.090*	−0.173**	−0.013	−0.171*
	(−1.759)	(−2.039)	(−1.869)	(−2.256)	(−0.230)	(−1.996)
FDI	−0.012	−0.008	−0.010	−0.008	−0.023	−0.009
	(−0.782)	(−0.545)	(−0.678)	(−0.512)	(−1.523)	(−0.605)
RD	0.207***	0.203***	0.204***	0.200**	0.190***	0.208***
	(7.249)	(2.685)	(7.273)	(2.618)	(6.886)	(2.670)
EDU	−0.525**	0.032	−0.499**	0.034	−0.577***	0.039
	(−2.585)	(0.058)	(−2.435)	(0.062)	(−2.781)	(0.070)
FEs	Yes	Yes	Yes	Yes	Yes	Yes
Adj R^2	0.906	0.798	0.908	0.799	0.902	0.798
F-statistics	16.773***	3.277***	17.678***	3.658***	15.882***	5.316***
Observations	180	90	180	90	180	90

Notes: t-statistics are in brackets. $^*p < 0.1$,$^{**}p < 0.05$,$^{***}p < 0.01$.

5.4. Robustness tests

We next conduct several robustness tests to validate our baseline regression results. We first introduce electricity production (EL) and the structure of renewable energy consumption (EC) as alternative dependent variables. The estimations for these two specifications are presented in Columns (1) and (2) of Table 4. Second, we replace GDF with an alternative green digital financial index (GDF_other), which is constructed using the coefficient of variation method as the weighting method. The results for this specification are presented in Column (3) in Table 4. In general, the significance and direction of the coefficients align closely with those observed in the benchmark results, reinforcing the robustness and reliability of our baseline findings.

Potential endogeneity issues could arise from unobserved factors, introducing estimation bias. To mitigate this concern, we introduce a lagged version of GDF (L.GDF) into the benchmark model. The coefficients of L.GDF are negative and statistically significant at the 1 % level (as shown in Column (4) of Table 4), denoting a consistent impact of GDF on EP over time. Additionally, we employ the system GMM to further validate our findings. The results in Column (5) of Table 4 confirm the statistical validity of the instruments through AR(2) and Hansen tests. In summary, these results reaffirm that GDF negatively impacts EP, bolstering the credibility of our initial conclusions.

5.5. Transmission channels of GDF on EP

The previous section examines the beneficial influence of promoting GDF on alleviating EP, indicating that this effect may be attributable to improved energy systems and advanced financial sector functionality. We next investigate the transmission channels through which GDF

Table 3
Heterogeneity due to different economic, financial, and technical conditions.

Variable	(1) LGDP	(2) HGDP	(3) LFS	(4) HFS	(5) LRD	(6) HRD
GDF	−0.312	−0.270*	−0.050	−0.576***	−0.239	−0.528***
	(−0.703)	(−1.846)	(−0.182)	(−2.722)	(−0.515)	(−3.523)
PGDP	−0.554**	−0.132	−0.588**	−0.199	−0.479**	0.152
	(−2.016)	(−0.738)	(−2.254)	(−1.112)	(−2.036)	(0.905)
FS	−0.183**	−0.049	−0.204**	−0.030	−0.130	−0.123
	(−2.353)	(−0.586)	(−2.127)	(−0.410)	(−1.646)	(−1.313)
FDI	−0.006	−0.018	−0.013	−0.002	−0.001	−0.061***
	(−0.347)	(−1.006)	(−0.709)	(−0.136)	(−0.055)	(−5.049)
RD	0.164***	0.223***	0.101***	0.128***	0.181***	0.150***
	(2.900)	(5.192)	(2.880)	(3.153)	(3.304)	(2.767)
EDU	−0.185	−0.568**	−0.110	−0.285	−0.312	−0.085
	(−0.477)	(−2.076)	(−0.464)	(−0.680)	(−0.768)	(−0.400)
FEs	Yes	Yes	Yes	Yes	Yes	Yes
Adj R^2	0.826	0.917	0.946	0.871	0.792	0.836
F-statistics	2.773**	11.809***	3.760***	3.788***	3.800***	19.198***
Observations	135	131	133	133	131	134

Notes: t-statistics are in brackets. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 4
Robustness test results with measurement and endogeneity issues.

Variable	Measurement issues			Endogeneity issues	
	(1)	(2)	(3)	(4)	(5)
L.EP					0.985***
					(15.437)
L.GDF				−0.555***	
				(−3.364)	
GDF	−1.118**	−0.123**			−0.105**
	(−2.497)	(−2.154)			(−2.477)
GDF_other			−0.315*		
			(−1.673)		
PGDP	0.245	−0.010	−0.372***	−0.408**	0.024
	(0.975)	(−0.231)	(−2.907)	(−2.576)	(0.763)
FS	−0.254**	−0.039*	−0.076*	−0.111**	0.013
	(−2.419)	(−1.804)	(−1.683)	(−2.093)	(0.227)
FDI	−0.008	0.013***	−0.009	−0.003	−0.002
	(−0.507)	(2.976)	(−0.919)	(−0.284)	(−0.260)
RD	−0.000	0.008	0.194***	0.203***	0.021
	(−0.006)	(0.609)	(7.279)	(7.261)	(1.540)
EDU	−0.942**	−0.069	−0.384	−0.306	−0.161*
	(−1.972)	(−0.802)	(−1.562)	(−1.238)	(−1.733)
FEs	Yes	Yes	Yes	Yes	Yes
Adj R^2	0.981	0.902	0.885	0.886	–
F-statistics	3.086***	3.100***	13.127***	14.837***	–
AR(2)	–	–	–	–	0.265
Hansen	–	–	–	–	0.703
Observations	270	270	270	240	240

Notes: t-statistics are in brackets. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

alleviates EP. First, sustainable advancement across all domains of finance is a crucial catalyst that doubles energy utilization efficiency. Financial development has been demonstrated to broaden the horizons of the renewable energy industry, foster energy technology innovation, and accelerate energy transition (Yang et al., 2021; Lee et al., 2023; Shahbaz et al., 2022; Meng and Qu, 2022), opening possibilities for addressing EP through improved energy efficiency. Therefore, we employ energy intensity (EI) as a mediating variable.

Second, integrating DF and GF initiatives drives digitalization forward. GDF leverages digital tools to develop environmentally friendly financial products and services that foster broader adoption of digitalization. Given its information-based nature, GDF is a catalyst for digitalization; therefore, we use digitalization level (DIF) as a mediating variable. We use Eq. (2) to perform the mediating effect analysis, incorporating the same control variables in the baseline regression. The results are presented in Table 5.

To analyze the mediating influence of EI, Column (1) of Table 5 estimates the impact of GDF on EI, and Column (2) evaluates the combined effects of GDF and EI on EP. The findings reveal that the coefficient of GDF is notably negative for EI and EP, while EI exhibits a significantly positive effect on EP. This indicates that the rapid expansion of China's GDF can mitigate EP by improving energy efficiency, supporting Hypothesis 2.

Possible rationale for how GDF improves energy efficiency includes directing financial resources toward green enterprises while constraining lending to fossil fuel–dependent industries (Yang et al., 2021; Lee and Lee, 2022). As Acemoglu et al. (2016) noted, the beneficial effects of renewable energy development on energy utilization efficiency lend further credence to this association. Overall, GDF has a crucial influence on EP by promoting technological innovation and advancing renewable energy sources (Chen et al., 2021; Sun et al., 2022; Wang and Wang, 2021). This facilitates the shift toward sustainable energy practices, ultimately aiding the alleviation of EP in China.

Table 5
Transmission channels: the roles of environmental and technical development.

Variable	Mediator = EI		Mediator = DIF	
	(1) EI	(2) EP	(3) DIF	(4) EP
GDF	−55.750*	−0.269**	46.149***	−0.280*
	(−1.923)	(−1.971)	(3.136)	(−1.967)
EI		0.002***		
		(4.127)		
DIF				−0.002**
				(−2.349)
PGDP	−140.286***	−0.141	51.020***	−0.286**
	(−6.400)	(−1.121)	(4.401)	(−2.363)
FS	−10.080	−0.067	10.475***	−0.066
	(−1.103)	(−1.519)	(3.016)	(−1.426)
FDI	1.751	−0.011	0.183	−0.008
	(1.642)	(−1.550)	(0.260)	(−1.080)
RD	−10.226*	0.210***	3.038	0.198***
	(−1.724)	(8.092)	(1.271)	(7.523)
EDU	−51.444	−0.284	−1.195	−0.373*
	(−1.417)	(−1.498)	(−0.077)	(−1.933)
FEs	Yes	Yes	Yes	Yes
Adj R^2	0.972	0.894	0.998	0.888
F-statistics	9.457***	52.424***	9.175***	49.687***
Observations	270	270	270	270

Notes: t-statistics are in brackets. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Using digitalization as a mediator, Column (3) in Table 5 examines GDF's effects on DIF, while Column (4) evaluates the impact of both GDF and DIF on EP. The findings reveal that the coefficient of GDF is significantly positive for DIF and significantly negative for EP, while DIF has a significantly negative effect on EP. This indicates that improving China's GDF positively influences digitalization, which subsequently contributes to lower EP. The results above validate the role of GDF in enhancing technological innovation and facilitating digitalization, laying a solid foundation for poverty alleviation efforts, supporting Hypothesis 2.

5.6. Examining the role of climate risk

We investigate whether climate risk moderates the impact of GDF on EP by introducing the interaction term GDF × CRI, based on Eq. (2). Table 6 displays the estimation outcomes, with Column (1) representing the composite GDF index, and Columns (2) and (3) representing its subcomponents, GF and DF, respectively. The findings indicate that while the coefficient of GDF remains negative, with an overall impact on EP, the coefficient of the interaction term is statistically positive, suggesting that climate risk diminishes the alleviating effect of GDF on EP, serving as a mechanism for GDF to influence EP, which supports Hypothesis 3.

The results align with the outcomes of Lee et al. (2023) that climate risk has an adverse effect on GF accelerating energy transition. One potential explanation for this phenomenon is the impact of climate risks on GDF provisions. Repeated occurrence of climate crises disrupts the existing renewable energy supply. Consequently, the risk landscape linked to energy project investments introduces new considerations concerning climate risk into the risk factors of GF development. This uncertainty could deter potential investors, including pension funds and banks, from allocating resources to clean energy or grid infrastructure investments (Zhang et al., 2023). Furthermore, the resulting weakened external financing environment for businesses and enterprises in the energy industry could result in increased costs for developing renewable energy sources (Duan and Wang, 2018), ultimately hindering efforts to mitigate EP.

Table 6
A further examination of the impact that climate risk plays.

Variable	(1)	(2)	(3)
GDF	−0.491***		
	(−3.673)		
GDF × CRI	0.134***		
	(2.687)		
GF		−0.356***	
		(−3.732)	
GDF × CRI		0.056	
		(0.982)	
DF			−0.159
			(−0.829)
GDF × CRI			0.086***
			(2.652)
PGDP	−0.030	0.002	−0.028
	(−1.627)	(0.146)	(−1.485)
FS	−0.385***	−0.397***	−0.333***
	(−3.518)	(−3.630)	(−2.882)
FDI	−0.093**	−0.099**	−0.046
	(−2.473)	(−2.537)	(−1.012)
RD	0.182***	0.179***	0.173***
	(6.616)	(6.524)	(6.413)
EDU	−0.279	−0.271	−0.320
	(−1.107)	(−1.055)	(−1.303)
FEs	Yes	Yes	Yes
Adj R^2	0.891	0.889	0.887
F-statistics	11.811***	10.614***	10.547***
Observations	270	270	270

Notes: t-statistics are in brackets. *$p < 0.1$,**$p < 0.05$,***$p < 0.01$.

In summary, the impact of GDF on EP could be compromised as climate-related risks raise concerns for investors regarding energy projects. We use the dynamic panel threshold (DPT) model to gain additional insights into the influence of climate risk, setting CRI as the threshold variable. Before proceeding with the DPT model, it is essential to test for linearity and the existence of a threshold effect. To this end, we first conduct a fast bootstrap test (Seo and Shin, 2016) to assess potential nonlinearity in the relationship between GDF development and EP, which allows us to determine whether a threshold effect exists. We then conduct an estimation to assess the nonlinear link between GDF and EP, as depicted in Eq. (4).

As shown in Table 7, the bootstrap *p*-value is below a 1 % significance level, indicating that we can reject the null hypothesis of no threshold effect. Specifically, the test results for GDF, GF, and DF all exhibit significant threshold values when introducing climate risk as the threshold variable. These results confirm the nonlinear nature of the relationship and the presence of a threshold effect, supporting the appropriateness of employing a DPT approach in the subsequent analysis.

Table 8 presents the threshold values, corresponding confidence intervals, and estimated parameters in the DPT model. Columns (1) and (2) are the results regarding GDF's effect on EP, and Columns (3)–(6) present separate estimation results for the individual dimensions of the green and digital subcomponents, respectively. The findings suggest that when climate risk is low, GDF positively contributes to EP alleviation; however, as climate risk approaches the threshold value, this beneficial effect diminishes and GDF may even have an adverse impact. This outcome indicates that GDF is beneficial for EP alleviation when climate risk is low. Conversely, when climate risk reaches the threshold value, the EP-mitigation effect disappears and GDF can even have an unfavorable impact.

Our results align with Lee et al. (2021), who argued that renewable energy innovation has a positive impact on reducing EP in conditions of low climate risk. One possible explanation is that minor disruptions caused by climate conditions may not hinder energy projects' investment and construction. With the increased synergy between green and DF, the risks and costs associated with projects can be better controlled, mitigating the adverse effects of climate risks (Wu and Huang, 2022). However, when climate risk exceeds the threshold, significant climate-related uncertainties may alter the expectations associated with energy investments. This can hinder the effectiveness of GDF and energy infrastructure construction, exacerbating EP. Such nonlinear effects observed in the threshold model further emphasize that climate risk introduces a tipping point, beyond which the economic benefits of GDF in addressing EP cannot be realized. This creates a compelling case for developing more robust financial instruments tailored to withstand climate shocks to ensure that economic growth driven by GDF is sustainable in the long term.

6. Conclusions

The escalating challenge of EP exacerbates climate change and impedes the sustainable development of global economies and societies (Scarpellini et al., 2019). China is under intensified pressure to shift toward increased energy efficiency while simultaneously tackling the challenge of EP. This imperative has heightened the government's attention toward changes in its financial sector. In this context, China's emerging GDF (and sustainable green fintech) has gained significant traction, reflecting the country's commitment to sustainability. Recent initiatives have emphasized China's efforts to cultivate a broader GDF ecosystem, leveraging technological innovation to offer sustainability solutions across the financial system's sustainable fintech landscape.

Despite the promising potential of GDF for addressing EP, the literature on this topic remains remarkably scarce. Therefore, our study investigates GDF's influence on EP. Moreover, given the interconnected nature of financial development, technological innovation, energy

Table 7
Testing results for linearity and the threshold effect.

Dependent variable	Independent variable	Threshold variable	Threshold value	Standard errors	z	P > |z|	95 % Conf. interval	Bootstrap p-value for linearity test	Bootstrap
EP	GDF	Climate risk	1.105	0.126	8.80	0.000	[0.859, 1.351]	0.000	1000
EP	GF	Climate risk	0.294	0.089	3.30	0.001	[0.119, 0.468]	0.000	1000
EP	DF	Climate risk	0.990	0.234	4.23	0.000	[0.531, 1.448]	0.000	1000

Notes: $*p < 0.1$, $**p < 0.05$, and $***p < 0.01$.

Table 8
Estimated results from the threshold approach.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Below	Above	Below	Above	Below	Above
L.EP	0.982***	−0.550***	0.539**	0.109	0.963***	−0.228
	(5.381)	(−2.822)	(2.491)	(0.630)	(3.662)	(−1.406)
GDF	−0.754**	0.107				
	(−2.130)	(0.277)				
GF			0.126	−0.441**		
			(0.492)	(−1.975)		
DF					−0.351***	0.344***
					(−2.885)	(2.728)
PGDP	0.239	0.195	−0.064	0.092	0.138	0.053
	(1.509)	(1.217)	(−1.153)	(1.222)	(1.526)	(1.019)
FS	−0.022	−0.194	0.126**	−0.300***	0.018	−0.060
	(−0.415)	(−1.144)	(2.075)	(−3.320)	(0.237)	(−0.691)
FDI	0.030***	0.026	0.024**	−0.078***	0.019**	−0.022
	(2.929)	(1.095)	(2.383)	(−5.302)	(2.356)	(−0.944)
RD	0.042	−0.155**	0.129**	−0.040**	0.025	−0.039
	(0.749)	(−2.561)	(2.270)	(−2.284)	(0.717)	(−1.112)
EDU	0.957**	−1.647***	−1.105**	1.272***	0.784	−0.877**
	(2.465)	(−2.846)	(−2.175)	(4.675)	(1.532)	(−2.167)
Provinces	30		30		30	
Observations	270		270		270	

Notes: t-statistics are in brackets. $*p < 0.1$,$**p < 0.05$,$***p < 0.01$.

project construction, and energy system reliability, we further extend our investigation to explore the intrinsic transmission channels within the GDF–EP nexus, introducing a certain nuance to the previous literature. Specifically, we examine the mediating roles of energy efficiency and digitalization and the moderating/threshold effects of climate risk. Based on statistical data from 30 Chinese provinces from 2011 to 2020, this study provides insights into the complex dynamics of the GDF–EP nexus in China, drawing three notable conclusions and policy implications.

First, the benchmark results demonstrate that GDF development has a significant impact on mitigating EP. To fully leverage this impact, policymakers should prioritize initiatives to facilitate energy projects and support entrepreneurs who encounter difficulties in accessing GDF resources. This access will allow these entities to overcome financing constraints that can impede their efforts to secure funding for energy-efficient production and environmentally friendly activities. This targeted approach expedites the deployment of clean energy solutions, optimizes energy utilization efficiency, and ultimately contributes to achieving sustainable energy targets and alleviating EP. Moreover, the beneficial effect of GDF on EP mitigation is notably evident in China's eastern and central areas, while a less significant impact is observed in the western area. This spatial heterogeneity highlights the significance of considering regional variations in policy formulation to avoid exacerbating existing disparities. Our analysis also reveals that high-level economic growth, financial development, and technological progress are essential prerequisites for realizing the benefits of GDF in addressing EP. Accordingly, local governments should invest in capacity-building programs to enhance absorptive capacity and facilitate the effective use of GDF resources.

Second, GDF affects EP by enhancing energy efficiency and deepening digitalization. Our mediating effect analysis indicates that improved energy efficiency mediates the GDF–EP nexus, suggesting that policymakers should prioritize initiatives to improve energy utilization efficiency as an aspect of GF development efforts to alleviate EP and integrate efficiency improvements in the energy field via GDF initiatives. GDF can deepen digitalization, which is conducive to addressing EP. In essence, achieving high-efficiency sustainable energy growth requires the driving forces of digital technology innovation and fintech expertise. Therefore, governments should prioritize increasing digitalization in consumption, production, and investments through the application of DF tools. This requires the establishment of an enabling environment for fintech startups and leading technology companies, fostering information technology innovation, and encouraging collaboration between the public and private sectors. By doing so, China will be capable of unlocking the full potential of GDF and fintech for addressing EP and driving the SDGs.

Third, climate risk moderates the mitigating effect of GDF on EP. Our threshold model analysis demonstrates that GDF could inhibit EP under certain climate risk thresholds. These results indicate that all countries should consider climate risk when developing GDF to support EP mitigation. Therefore, policy designs must incorporate risk assessment and management elements to ensure green projects can endure climate-related challenges. This requires strengthening resilience measures and cultivating the adaptive capacity to withstand climate-related shocks to ensure the sustainability of GDF interventions and mitigate the adverse effects of climate risk on EP alleviation.

Despite the comprehensive analysis presented in this study, several limitations should be acknowledged. First, this study relies on provincial-level data from China, which limits the generalizability of our findings. Future research could use cross-country comparisons or investigate regions with different institutional frameworks. Second, while we focus on key transmission channels, future research could investigate other mechanisms or risks such as policy shifts or market volatility. Additionally, the GDF indicators used in this study, based on transaction volumes and subindices of green and DF, could be further refined. Future research should consider integrating more comprehensive data sources, including quantitative metrics (e.g., firm-level data or more granular transaction details) and qualitative insights (e.g., case studies or expert evaluations). This would allow for a more comprehensive measure of GDF's impact, capturing direct financial flow and the broader socioeconomic outcomes linked to GDF-related initiatives.

CRediT authorship contribution statement

Chi-Chuan Lee: Writing – review & editing, Visualization, Supervision, Conceptualization, Investigation. **Mingyue Li:** Data curation, Investigation, Resources, Writing – review & editing. **Xinghao Li:** Writing – review & editing, Investigation, Conceptualization, Methodology, Software. **Hepeng Song:** Writing – original draft, Methodology, Investigation, Conceptualization, Visualization.

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Declaration of competing interest

The authors declare that we have no relevant or material financial interests that relate to the research described in this paper.

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Appendix A. Appendix

Table A1
Definition of variables and summary statistics.

Variable	Definition	Mean	p50	Maximum	Minimum	Std. Dev.
Dependent variable						
EP	Energy poverty	0.437	0.394	0.804	0.148	0.135
EL	Electricity production	2.749	2.841	4.077	0.548	0.745
EC	Electricity consumption structure	0.229	0.217	0.551	0.087	0.068
Core explanatory variables						
GDF	Comprehensive index of green digital finance	0.305	0.312	0.718	0.059	0.115
GF	Comprehensive index of green finance	0.182	0.164	0.645	0.042	0.089
DF	Comprehensive index of digital finance	0.480	0.519	0.920	0.023	0.212
Control variables						
PGDP	Per capita GDP	10.400	10.338	11.588	9.203	0.475
FS	Ratio of loans of banking institutions to GDP	4.923	4.893	5.552	4.206	0.298
FDI	Per capita FDI	6.462	6.716	9.049	1.588	1.353
RD	Full-time equivalent of R&D personnel	11.166	11.389	13.596	8.296	1.177
EDU	Average years of education	2.212	2.207	2.548	2.011	0.092

Table A2
Cross-correlations.

Variable	VIF	EP	GDF	PGDP	FS	FDI	RD	EDU
EP	–	1						
GDF	1.99	−0.350***	1					
PGDP	5.03	−0.493***	0.650***	1				
FS	2.44	0.006	0.480***	0.391***	1			
FDI	2.93	−0.582***	0.298***	0.674***	−0.063	1		
RD	2.72	−0.620***	0.297***	0.590***	−0.243***	0.657***	1	
EDU	2.71	−0.397***	0.510***	0.752***	0.353***	0.643***	0.432***	1

Note: *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.

Table A3
Green digital finance index construction.

Index	Indicator variable
1st sub-index: Green finance	
Green-related credit	Share of interest expenditure of the eight energy-intensive industries in above-scale industries
Green-related insurance	Share of agricultural insurance income in added-value in agriculture
Green-related investment	Investment in environmental infrastructure per capita

(continued on next page)

Table A3 (*continued*)

Index	Indicator variable
Green-related governance	Share of public expenditure on environmental protection
Green-related securities	Share of the market value of environmental protection companies
1st sub-index: Digital finance	
Digital-related credit	Frequency and quantity of credit used via Alipay
Digital-related insurance	Frequency and quantity of insurance use via Alipay
Digital-related investment	Frequency and quantity of investment use via Alipay
Digital-related monetary fund	Frequency and quantity of monetary fund use via Alipay
Digital-related payment	Frequency and quantity of payment use via Alipay

Table A4
Panel unit root tests.

Variable	LLC		Fisher-ADF	
	Stat.	P-value	Stat.	P-value
EP	−16.104***	0.000	96.037***	0.002
GDF	−7.439***	0.000	181.724***	0.000
PGDP	−4.901***	0.000	136.172***	0.000
FS	−10.563***	0.000	118.908***	0.000
FDI	−4.323***	0.000	118.083***	0.000
RD	−8.762***	0.000	87.203***	0.013
EDU	−22.498***	0.000	158.049***	0.000
CRI	−9.423***	0.000	170.739***	0.000

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.108144.

Data availability

Data are available from the authors upon request.

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