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Green Financing, Energy Transformation, and the Moderating Effect of Digital Economy in Developing Countries

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Abstract

The energy sector in many developing nations faces the difficulty of insufficient financing throughout the low-carbon transition, highlighting the importance of international green financing in alleviating financial constraints. The advancement of digital technology could facilitate green financing for energy transition in the digital economy, but this statement lacks empirical evidence. The primary objective of this research is to investigate the impact of international green financing on low-carbon energy transformation in developing nations. Additionally, we investigate the moderating role of digital economy between the two. Our findings validate the favorable impact of international green financing on low-carbon energy transformation, and this impact is particularly evident for hydro and wind energy consumption. We show that this beneficial effect is greater for low-income countries or regions with high levels of energy transition. We also provide evidence of the positive moderation effects of digital economy and find that its effects are still present in the transition to hydro and wind energy. This research helps to broaden green financing channels for the energy sector in developing countries, especially from the perspective of digital economy.

Keywords Green Financing · Low-carbon Energy Transformation · Digital Economy · Moderation Effect · Global case

JEL Classification Q42 · O33 · G23 · C23

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1 Introduction

Renewable energy has emerged as a pivotal element in the energy transition, driven by mounting global apprehension regarding climate change and environmental sustainability (Wei et al. 2023). Recently developed low-carbon energy technologies, such as those in solar, wind, and hydropower, have garnered considerable traction and acceptance (Li et al. 2023). The transition to low-carbon energy necessitates a departure from conventional high-carbon energy sources towards sustainable, low-emission alternatives like wind, solar, hydro, and biomass. These sources are abundant, cost-effective, and environmentally benign (Blazquez et al. 2020; Chen et al. 2022). Nonetheless, the shift towards low-carbon energy sources demands sustained and augmented investment (IEA 2022a). It is noteworthy that despite developing economies constituting two-thirds of the world's population, they represent only one-fifth of clean energy investments (IEA 2021). Accounting for only a quarter of the per capita emissions of developed countries, developing economies are projected to increase their carbon emissions by 5 gigatonnes over the next 20 years under current policy scenarios (IEA 2021). Therefore, supporting developing countries in enhancing their energy systems through robust green financing initiatives is crucial as they constitute the cornerstone of future emissions reduction efforts.

Developing economies face persistent challenges in mobilizing green financing for clean energy projects. The COVID-19 pandemic, alongside other socio-economic and climatic risks, exacerbates the challenge of accessing clean energy financing for developing economies, placing them at a disadvantage in steering the low-carbon energy transition (Oliyide et al. 2023). Public finance plays a crucial role in facilitating financeable renewable energy development projects for developing countries. The World Bank has allocated over $2 billion in financing for distributed renewable energy solutions, predominantly in sub-Saharan Africa. Nevertheless, by 2030, the global community will require $90 billion in public funding for clean energy innovation demonstration projects, whereas the current budget stands at only $25 billion (IEA 2022b; Li et al. 2023). Simultaneously, governments of developing countries are striving to expand access to finance and attract private investment for scalable renewable energy projects. This is crucial for the deployment of clean energy initiatives in vulnerable communities and remote areas of developing nations (Duran and Sahinyazan 2021).

International financing has greater potential for growth and research impact compared to domestic financing, which has been studied more extensively. Approximately 25% of energy investments in emerging economies are sourced internationally, a proportion expected to rise further (IEA 2021). Over the past two decades, there has been a clear trend of growth in international green financing available to developing countries to support clean energy research and development (R&D) and renewable energy production (see Fig. 1). However, there is still a lack of sufficient empirical evidence to support the contribution of international green financing in driving a low-carbon energy transition in developing countries. Investigating the role of international green finance in offering financing solutions for developing economies to facilitate the low-carbon energy transition constitutes a primary objective of this study.

The digital economy is experiencing widespread adoption and growth in emerging countries. Since the inception of the Digital India program in 2015, India has been actively cultivating its digital economy ecosystem, poised to generate a potential economic gain of

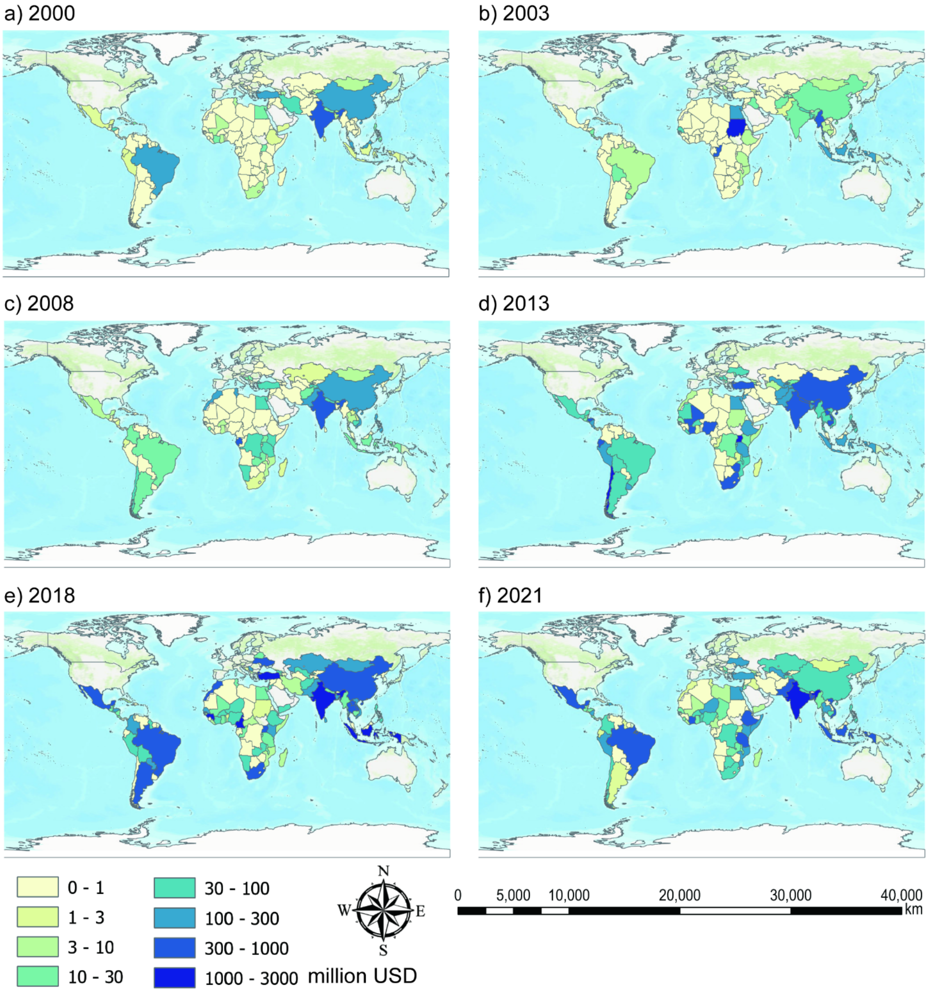

Fig. 1 Developing countries with access to green financing and green financing flows in specific years. Note: Relevant data are from OECD and IREAN and are expressed in constant 2020 USD

$1 trillion by 2025 (MEIT 2019). China's digital economy is projected to reach 50.2 trillion yuan (approximately $6.94 trillion) in 2022, boasting a nominal growth rate of 10.3% year-on-year (CAICT 2023). Numerous studies have demonstrated that the digital economy is emerging as a crucial facilitator of the low-carbon transition (Hwang 2023). Long-term information and communications technology (ICT) development can contribute to driving green energy production in a country, particularly when factoring in installation costs (Luo et al. 2024). On the other hand, digital economy and technology have the potential to influence the development of green finance by fostering technological innovation and enhancing linkages among market participants (Huo et al. 2022; Kumar et al. 2022). Enhanced information sharing and cost control are recognized as significant benefits of the digital economy in addressing the limitations of traditional finance in advancing the energy transition (Tang et al. 2022). Investigating the influence of digital economy development on the advantages of green finance within the energy transition framework constitutes another primary objective of this work.

Previous studies have extensively investigated the connections between green financing and energy transition (Bai and Lin 2023), energy retrofitting (Caporale et al. 2023; Zhang et al. 2022a), and green transformation (Wang et al. 2021, 2022). Existing literature predominantly focuses on domestic financing. As mentioned previously, international financing flows have emerged as a key strategy for addressing the financing of clean energy projects in developing countries. However, existing studies have provided limited quantitative analysis regarding the scale of the impact of international green financing. On the other hand, there remains a lack of empirical evidence on the interaction between the digital economy and green financing amidst the context of low-carbon transition and the rapid development of digital technologies. To address these research gaps, we utilize panel data from 32 countries spanning the period from 2003 to 2020 to investigate the relationship between international green financing and the low-carbon energy transition. Additionally, we explore the impact of the digital economy on the transition to low-carbon energy, with a focus on its moderating effects. Moreover, we assess how the impact of green finance on low-carbon energy transition varies across different income groups and employ panel quantile regressions to explore potential nonlinear effects.

This paper contributes twofold to the existing literature. Firstly, it underscores the effectiveness of green financing in tackling the financing challenges linked with the low-carbon energy transition in developing nations. Specifically, our study reveals that green financing yields favorable outcomes primarily in the wind and hydro energy sectors. This insight offers valuable guidance for policymakers and financial institutions to reshape the financial landscape and enhance the efficiency of green financing. Secondly, our study confirms the beneficial moderating effect of digital economy on this relationship and discerns and compares variations across energy types. This insight highlights the significance of the digital economy in enhancing the efficiency of green financing. Our findings offer crucial implications for advancing the low-carbon energy transition, particularly through the perspective of digital economy.

The remainder of this work is as follows. Section 2 reviews relevant literature and highlights the gaps. Section 3 describes the methodology and data. Section 4 presents the empirical findings. Section 5 explores the moderation effects of digital economy. Section 6 presents the main findings and insights for policy implementation.

2 Literature Review

2.1 The Nexus Between Green Financing and Low-carbon Energy Transition

Green finance has increasingly garnered widespread attention as a key mechanism for promoting low-carbon development (Du et al. 2023; Ren et al. 2023; Zhang et al. 2022a; Zhao et al. 2023b). Belgacem et al. (2023) evaluate the effectiveness of green bond financing in fostering environmental investment in emerging Asian countries. Their findings suggest that green bonds positively influence long-term investments and loans for renewable energy, thereby facilitating the transition to low-carbon energy sources. Both the public and private sectors play crucial roles in the investment process. Polzin et al. (2021) argue that both governments and private investors must continue their investments to achieve a transition to carbon-emission-free power systems. Aleluia et al. (2022) emphasize the importance of government and public policies in accelerating the sustainable energy transition in Southeast Asia, particularly in deploying financeable clean energy projects.

Developments in the financial sector have facilitated the financing of cleaner projects. Kim and Park (2016) demonstrate that the renewable energy industry, which relies heavily on external financing, is experiencing a positive growth trajectory within the broader context of financial development. Well-established financial markets can accelerate the growth of renewable energy industry, particularly when utilizing debt and equity financing (Kim and Park 2016). Brunnschweiler (2010) discovers that robust capital markets can effectively channel private investment into the renewable energy industry, while ineffective financial markets yield the opposite outcome. Hall et al. (2017) observe that leveraging financial markets as an adaptation mechanism can broaden the impact of low-carbon investment policies. Financial institutions have a responsibility to optimize the capital allocation to enhance social benefits and mitigate environmental damage (Lioui and Sharma 2012).

Green financing frequently faces uncertainty. Caporale et al. (2023) argue that small and medium-sized firms in Europe tend to be influenced by different sources of funding, which in turn affects their willingness to conserve energy. The finding demonstrates that internal financing consistently positively influences enterprises' inclination to take up energy-saving methods. Zhang et al. (2022a) examine how energy financing affects energy transformation amid the COVID-19 pandemic, and take green bond financing as an intervention measure. They find that in E-7 economies, energy financing heavily depends on green bonds, emphasizing the key role of green bonds in energy transformation. Polzin and Sanders (2020) evaluate the financing sources for clean energy in Europe and reveal that current financing sources can provide 2–6 times the required funding. Nevertheless, the anticipated disruptions in policies have resulted in reluctance among institutional investors and borrowers, particularly pension funds and financial institutions, to allocate funding towards renewable energy or grid infrastructure.

Building on the preceding analysis, we propose the initial research hypothesis:

H1 *Green financing facilitates the transition to low-carbon energy.*

2.2 The Influence of Digital Economy on the Nexus Between Green Financing and Low-Carbon Energy Transition

The digital economy, as an emerging resource, is increasingly serving as a crucial catalyst for future progress (Huo et al. 2022). The Internet has contributed to the advancement of green finance by offering novel technology advancements and enhancing relationships among market participants (Huo et al. 2022; Kumar et al. 2022). Digitization's fast, open, and porous nature can assist financial markets in allocating resources more rationally (Bris et al. 2017). The Internet plays a crucial role in the financial sector due to its utilization in digital payment and trading systems, including big data technologies and E-commerce (Lin et al. 2015). According to Cheng et al. (2018), the Internet, particularly online financial trading platforms, significantly influences the functioning of the stock market. The digital economy combined with finance can incentivize environmental technology by facilitating information accessibility (Yu et al. 2020).

The literature has extensively examined the influence of digital economy on transition to the low-carbon system. Zhang et al. (2022b) employ provincial panel data spanning from 2007 to 2019 to assess China's digital economy system. Their findings indicate that the digital economy is emerging as a significant catalyst for low-carbon development. Tao et al. (2022) highlight that Fintech has a beneficial effect on promoting the economic transformation of carbon regulation and greenhouse control. Hwang (2023) posits that digital economy is a key instrument for expediting and expeditiously attaining a low-carbon economic transition. This transformation is vital to avert disastrous repercussions and guarantee environmental sustainability. In this context, the participation and technological upgrading of the green financial system are crucial for strengthening energy control (Huo et al. 2022). This means that digital economy's advancement enables green financial system to effectively assist the technological enhancement of low-carbon transformation.

Hence, we present our second hypothesis.

H2 *The digital economy helps to drive the low-carbon energy transition and effectively enhances the role of green financing in this process.*

2.3 Research Gaps

Our comprehensive literature analysis reveals several critical research gaps requiring immediate attention. Firstly, existing research inadequately explores the impact of global green financing on the low-carbon energy transition in developing countries. It is crucial to investigate the influence of international green financing on the transition to renewable energy and to compare its effects across different energy types. Additionally, although previous literature has explored the potential impacts of digital economy on the transition to low-carbon systems, there is a notable absence of research specifically investigating the role of digital economy in the connection between green financing and energy transition. Research in this area helps to uncover the advantages of leveraging digital economy to facilitate the financing of clean energy projects, thus expediting the transition to low-carbon energy.

3 Model Construction and Data Sources

3.1 Econometric Model

3.1.1 Modeling the Effect of Green Financing on Low-carbon Energy Transition

To examine the role of green financing in facilitating the low-carbon transition of energy sector in developing countries, we construct an econometric model. We also incorporate controls for various economic and social factors affecting the low-carbon energy transition to address concerns related to endogeneity stemming from omitted variable bias. We employ an econometric theoretical model to assess the influence of green financing on the low-carbon energy transition, as illustrated in Eq. (1).

$$rc_{i,t} = \alpha + \beta * gf_{i,t} + \gamma_j * X_{j,i,t} + \nu_i + \mu_t + \varepsilon_{i,t} \tag{1}$$

In the model, rc refers to renewable energy consumption (TWh), which includes biomass energy (denoted as bc), hydro energy (hc), solar energy (sc), and wind energy (wc). It serves as a proxy variable for the low-carbon energy transition. gf refers to the flow of clean energy financing obtained by developing countries (million USD) and represents the level of green financing. X_j stands for control factors including economic development (measured by per capita gross domestic product (GDP) (USD), denoted as eco), industrialization process (measured by the proportion of industrial added value to GDP (%), denoted as ind), urbanization rate (measured by the proportion of urban population to total population (%), denoted as urb), foreign direct investment (measured by the proportion of foreign direct investment to GDP (%), denoted as fdi), population density (measured by the number of people per square kilometer (people/sq km), denoted as pop), coal rent (measured by the proportion of coal rent to GDP (%), denoted as $coal$), and readiness for climate change adaptation (measured by the climate change adaptation readiness index, denoted as $read$). Subscripts i and t denote country and year, respectively. Coefficients α, β, γ_j represent variable coefficients, while ν_i and μ_t signify individual and year fixed effects, and $\varepsilon_{i,t}$ refers to the random disturbance term. We focus on the coefficient of independent variable β. A significant and positive coefficient (β) indicates that green financing promotes the transition to low-carbon energy, thus validating hypothesis ***H1***.

3.1.2 Modeling the Moderating Effect of Digital Economy

Another objective is to examine the moderating effect of digital economy on the correlation between green financing and low-carbon energy transition. To accomplish this, we integrate digital economy and the interaction term between digital economy and green financing into the model outlined in Eq. (1), as depicted in Eq. (2).

$$rc_{i,t} = \delta + \theta * gf_{i,t} + \kappa_j * X_{j,i,t} + \eta * de_{i,t} + \omega * de_{i,t} * gf_{i,t} + \nu_i + \mu_t + \varepsilon_{i,t} \tag{2}$$

In this equation, de represents the level of the digital economy in each country, measured using the digital economy index obtained through the method of fully-aligned polygonal graphical indexing. δ, θ, κ_j, η, and ω represent the coefficients to be estimated. The meanings of the remaining symbols remain consistent with Eq. (1). Of particular interest is the coefficient ω, which corresponds to the interaction term between de and gf. A significant ω suggests the presence of a moderating effect of digital economy. If both ω and θ exhibit a positive sign, it indicates that the digital economy amplifies the beneficial impact of green financing on the low-carbon energy transition, thereby validating ***H2***. The coefficient η represents the direct influence of digital economy on the low-carbon energy transition.

3.2 Data

We utilize an unbalanced panel dataset comprising 32 developing countries globally, spanning the period from 2003 to 2020. The data is sourced from authoritative institutions such as British Petroleum (BP), the Organization for Economic Co-operation and Development

(OECD), the International Renewable Energy Agency (IRENA), the World Bank, and the International Telecommunication Union. Samples with severe missing data are excluded from the analysis. To ensure data integrity, linear interpolation is employed to fill in missing values for select variables related to renewable energy consumption. For instance, following interpolation, the observations for sc increase from 559 to 568, while bc fills in 24 missing values. Additionally, to mitigate price volatility disruptions, all price data are converted to 2015 constant prices using the deflator. Consequently, the dataset comprises 568 observations.

3.2.1 Low-carbon Energy Transition data

We employ statistical data on renewable energy consumption (including biomass, hydro, solar, and wind energy) from the BP Statistical Review of World Energy[1], as well as statistical data on renewable energy electricity consumption (including biomass, hydro, solar, and wind electricity) from both the BP Statistical Review of World Energy and the Ember Global and European Electricity Review[2], as alternative variables for the dependent variable to directly measure the low-carbon energy transition. These indicators effectively capture the commitment of developing countries to adopt renewable energy, reflecting their pace and advancement in transitioning from high-carbon to renewable (low-carbon) energy sources, a common approach in existing literature (Li et al. 2023; Zeng et al. 2024).

3.2.2 Green Financing data

SDG 7a emphasizes the need for enhanced international collaboration to bolster investment in energy infrastructure and clean energy technologies (United Nations 2017). This metric, aligned with goal 7a, quantifies international financial inflows directed towards developing nations to foster clean energy R&D and promote renewable energy generation, including hybrid systems. The dataset, jointly curated by the OECD[3] and the IRENA[4], encompasses official loans, grants, and equity investments for clean energy R&D and renewable energy production from foreign governments, multilateral agencies, and other development finance institutions, encompassing both official and private flows. Data is organized by country at the project level and meticulously scrutinized for accuracy. However, it currently does not comprehensively capture all financial flows, with investments in off-grid electricity supply and improved cookstove projects only partially accounted for. Nonetheless, this indicator stands as a robust measure for assessing the progression of international green financing. The global advancement of green financing is visually depicted in Fig. 1. Notably, developing countries have witnessed a substantial uptick in access to international clean energy finance, particularly evident in select nations and regions across South Asia and South America.

[1] See https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

[2] See https://ember-climate.org/insights/.

[3] See https://data.oecd.org.

[4] See https://www.irena.org/Data.

3.2.3 Socio-economic data

To ensure precise estimates of the impact of green financing, we extensively account for the influence of other economic and social factors on the low-carbon energy transition. Economic growth in a country influences investors' expectations regarding the returns from clean energy projects, typically facilitating the financing of such projects (Taghizadeh-Hesary and Rasoulinezhad 2020), thereby attracting additional capital for the low-carbon transition. Economic growth is quantified using GDP per capita.

Shahbaz et al. (2022) argue that transforming and upgrading the industrial structure can diminish reliance on fossil fuels, thereby facilitating the low-carbon transition. We incorporate the industrialization process as a control variable and measure it using the ratio of industrial value added to GDP.

The level of foreign direct investment (FDI) is measured as the ratio of net FDI inflows to GDP. FDI plays a crucial role in enhancing the efficiency of renewable energy production through technology transfer to the economy (Paramati et al. 2017). Their study highlights the significant impact of FDI on the adoption of sustainable energy practices.

Population density refers to the number of people per unit area, measured in square kilometers. It serves as a key determinant of energy consumption patterns, exhibiting a robust correlation with both overall energy usage and renewable energy consumption. Numerous studies have demonstrated that higher population density tends to correlate with lower energy consumption (Kamal-Chaoui and Robert 2009).

The urbanization rate is determined by the proportion of urban population to total population. Research conducted by Yin and Qamruzzaman (2024) confirms a correlation between urban sprawl and increased energy demand, with a noted trend towards renewable energy adoption to address this demand.

Rental fees are significant in energy extraction processes. Increased conventional energy rents often incentivize mineral firms to intensify fossil fuel extraction (Asongu et al. 2020; Wang et al. 2020), potentially hindering the transition to renewable energy. Hence, coal rent is incorporated into the model as a control variable, quantified by its share in GDP.

Governmental renewable energy strategies may be influenced by existing policies and climate initiatives. Considering the challenge of integrating varied energy and climate policies from developing countries into the model, we opt to control for climate change adaptation readiness as an indicator of policy effectiveness or response, aiming to capture the broader impact of policy initiatives across nations. Sarkodie et al. (2023) underscore the significance of climate change adaptation readiness in steering the transition towards renewable energy sources.

Raw data for the above control variables are available from the World Bank database[5].

3.2.4 Digital Economy data

To assess the scope of digital economy, we utilize the indicator framework developed by Shahbaz et al. (2022), which comprises four dimensions: digital infrastructure, digital social impact, digital trade, and digital social support, encompassing a total of 11 sub-indicators (refer to Fig. 2). Subsequently, we compute the digital economy index utilizing a fully-aligned polygonal graphical indexing method, which leverages expert assessment to effec-

[5] See https://databank.worldbank.org/reports.aspx?source=World-Development-Indicators.

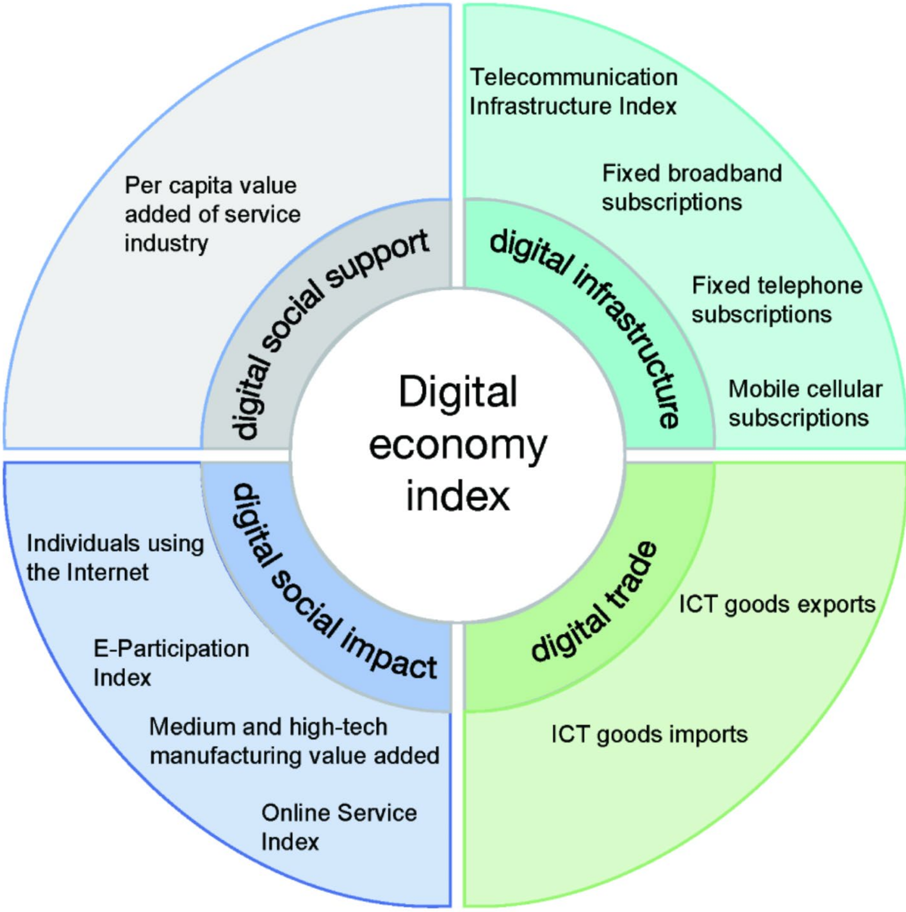

Fig. 2 System of indicators for calculating the digital economy index

tively mitigate subjective random errors (Hao et al. 2020; Wu et al. 2005). The data utilized in this analysis is sourced from databases including the World Bank[6], the International Telecommunication Union[7], and the UN E-Government Knowledgebase[8].

Definitions and descriptive statistics for the variables used in the study are outlined in Table 1. Before conducting empirical analysis, we test for multicollinearity in the model, as shown in Table A1. The general rule of thumb is that if the variance inflation factor (VIF) is less than 10, the model is not considered to have serious multicollinearity issues. The results indicate that there is no serious multicollinearity concern among the variables used in this study.

[6] See https://databank.worldbank.org/reports.aspx?source=World-Development-Indicators.

[7] See https://www.itu.int/en/Pages/default.aspx.

[8] See https://publicadministration.un.org/egovkb.

Table 1 Definitions and descriptive statistics of the selected variables

Variable	Definition	Mean	Std. Dev.	Min	Max	Data source
rc	Renewable energy consumption (TWh)	195.2	612.7	0.009	5,838	BP
bc	Biomass energy consumption (TWh)	14.92	41.17	0	264.5	BP
hc	Hydro energy consumption (TWh)	148.9	444.7	0	3,471	BP
sc	Solar energy consumption (TWh)	6.462	46.82	0	685.7	BP
wc	Wind energy consumption (TWh)	17.89	98.20	0	1,225	BP
re	Renewable power consumption (TWh)	68.29	221.1	0	2,185	BP
be	Biomass power consumption (TWh)	3.977	12.51	0	135.6	BP
he	Hydro power consumption (TWh)	54.45	164.5	0	1,322	BP
se	Solar power consumption (TWh)	2.391	17.61	0	261.1	BP
we	Wind power consumption (TWh)	6.682	37.03	0	466.5	BP
gf	Green finance received by developing countries for clean energy (million USD)	128.6	284.2	0	2,640	OECD; IRENA
gfp	Green finance as a percentage of GDP (‰)	0.509	1.761	0	33.04	Calculation
de	Digital economy index	0.389	0.244	0.0107	1.114	Calculation
eco	GDP per capita (USD)	5,441	3,537	698.7	18,651	WDI
fdi	Foreign direct investment as a percentage of GDP (%)	3.050	4.348	− 7.021	55.07	WDI
pop	Population density (people/sq km)	144.6	214.0	5.522	1,286	WDI
urb	Urbanization rate (%)	58.88	18.05	18.20	92.11	WDI
ind	Industrial value added as a percentage of GDP (%)	33.97	10.29	17.98	70.84	WDI
coal	Coal rent as a percentage of GDP (%)	0.367	0.800	0	7.248	WDI
read	Climate change adaptation readiness index	0.379	0.0744	0.206	0.579	ND-GAIN

The table provides detailed information on the variables used in the study, including their definitions, units, mean values, standard deviations, minimum and maximum values, and the sources of data. The digital economy index is derived using a fully-aligned polygonal graphical indexing method. Std. Dev. refers to standard deviation

3.3 Estimation Strategy

We utilize a range of estimation techniques to accurately assess the relationship between green financing, the digital economy, and the low-carbon energy transition. Initially, we establish the preliminary link between green financing and the low-carbon energy transition through Ordinary Least Squares (OLS) estimation, which assumes that all sample observations are generated by the same process. Subsequently, we employ Random Effects (RE) and Fixed Effects (FE) models to further investigate, accounting for individual effects. These models differ in their treatment of individual effects: the RE model assumes these effects are uncorrelated with the explanatory variables, whereas the FE model considers them to be correlated with the randomized disturbance term, assigning each individual a non-randomized intercept term. The Hausman test aids in determining the correlation between individual effects and explanatory variables, thus guiding the estimation strategy.

Addressing endogeneity is crucial for obtaining reliable estimates of models (1) and (2). Sources of endogeneity in this study may include omitted variables and bidirectional causality. To mitigate endogeneity resulting from omitted variables, we control for economic and social factors that may influence the low-carbon energy transition, encompassing various dimensions such as economic trade, population, urbanisation, industrialisation, fossil fuels, and climate policy. Additionally, the two-way fixed effects model specification helps us eliminate the potential impact of "time-invariant individual characteristics" and "individual-invariant time characteristics" on model estimation, thereby reducing endogeneity issues caused by omitted variables.

Moreover, the adoption of renewable energy is likely to influence investment decisions positively. Zhong et al. (2024) demonstrate that increased renewable electricity output stimulates investment in renewable energy, indicating its impact on domestic investors' choices. Likewise, international investors may prefer countries showcasing potential or commitment to renewable energy adoption, driven by factors like risk reduction, enhanced reporting opportunities, and alignment with sustainability objectives. However, this situation raises concerns regarding endogeneity resulting from bidirectional causality. To further address this issue, employing suitable instrumental variables becomes imperative. We employ a creative approach, using the square of the mean level of green financing in all other countries during the same year (denoted as $mean\_gf2$) as an instrument, and employ two-stage least squares (2SLS) estimation.

The construction of this instrument was inspired by previous studies (Chen et al. 2024; Liu et al. 2024; Xiang et al. 2023; Yu et al. 2020; Zhao et al. 2023a). Using the square term helps capture the nonlinear effects in the distribution of international clean energy funds, i.e., the marginal effect of changes in the green financing levels of other countries on the support received by the home country. For instance, when other countries receive a small amount of green financing, changes in their levels may have a minor impact on the home country's support; however, when other countries receive significant financing, changes in their levels may have a substantial impact on the home country.

First, this instrument ensures correlation with the endogenous explanatory variable, which may arise from potential competition effects or spillover effects. The competition effect implies that developing countries may compete for green financing during the same period (Dreher et al. 2021). The spillover effect implies that when the global total amount of green financing increases, all countries may benefit, leading to an increase in the financing received by each country.

Second, considering that the green financing levels in other countries typically do not directly affect the home country's low-carbon transition process, there are compelling reasons to regard the instrument as exogenous. Green financing decisions are primarily driven by factors such as project costs, environmental benefits, and inherent characteristics of the beneficiary country (including resource endowment, governance level, and financial development) rather than the low-carbon energy transition process in other countries (Benavides-Franco et al. 2023).

Moreover, the monotonicity assumption of the instrumental variable emphasizes that the direction of the instrument's effect is consistent across all individuals (Angrist and Pischke 2009). We plot the relationship between the endogenous explanatory variable gf and the instrument $mean\_gf2$ by region and income, as shown in Fig. 3. It can be observed that the slopes of the fitted lines between gf and $mean\_gf2$ are positive in all groups. This indicates that the instrument's effect on green financing is consistent across all countries, supporting the monotonicity assumption of the instrument. However, the varying response intensities (different slopes in different groups) reveal heterogeneous effects of the instrument. Furthermore, this positive correlation may suggest that the spillover effect plays a more significant role compared to the competition effect.

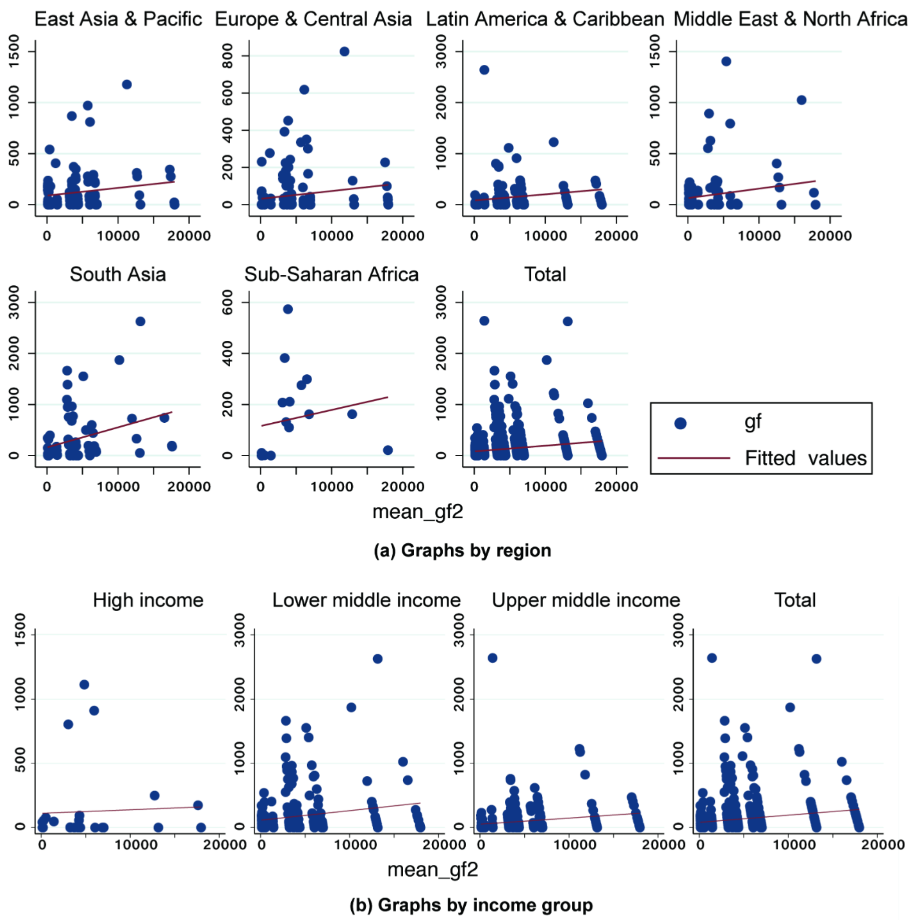

Fig. 3 Relationship between gf and mean_gf2, by region and income group

In this study, instrumental variable (IV) regression using two-stage least squares, while controlling for year and country-specific effects, serves as the primary estimation approach. The subsequent statistical tables present the Kleibergen-Paap rk Wald F-statistic to assess instrumental correlations and the Kleibergen-Paap rk LM statistic to ensure instrument identifiability. A p-value of less than 0.01 for the Kleibergen-Paap rk LM statistic indicates that the null hypothesis of "instruments are unidentified" is rejected at the 1% significance level. If the Kleibergen-Paap rk Wald F statistic exceeds the critical values provided by Stock and Yogo (2005), it suggests that the instruments are correlated with the endogenous explanatory variables and are not weak instruments. We present the estimation strategy of this study in Fig. 4.

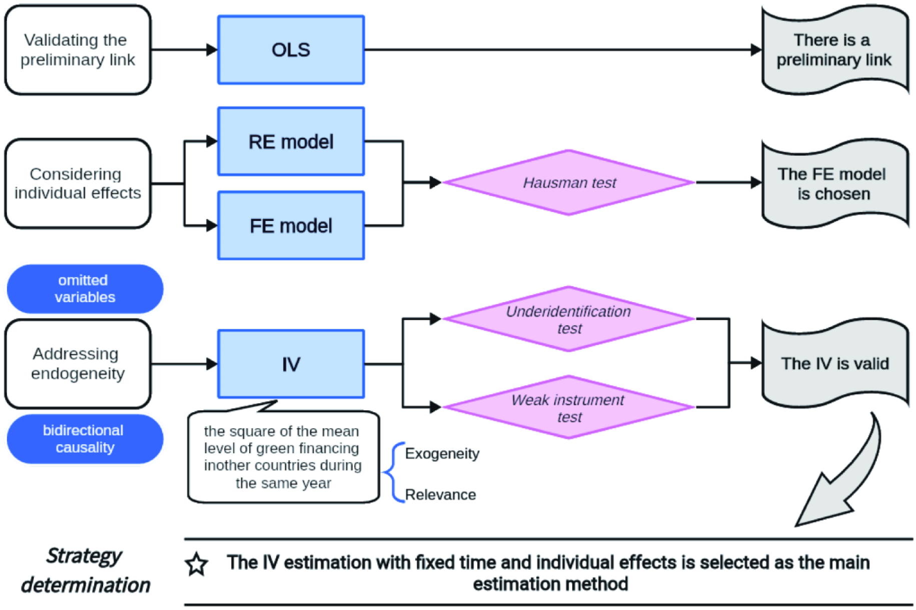

Fig. 4 Estimation strategy for this research

4 Effect of Green Financing on the Low-carbon Energy Transition

4.1 Benchmark Results

4.1.1 FE Estimates

Based on OLS, RE, and FE estimations, OLS confirms the progressive impact of green financing on the low-carbon energy transition. The Hausman test results validate significant correlations between individual effects and explanatory variables (Prob > chi2 = 0.0000). Consequently, to ensure a consistent estimator, we choose the FE model over the RE model. Table A2 presents both OLS and RE estimation outcomes, while Table 2 displays FE estimates, including the influence of green financing on renewable energy consumption and various sources (biomass, hydro, solar, and wind energy). Year and country are simultaneously fixed to control for constant year effects and individual characteristics. FE model results demonstrate a statistically significant and positive relationship between green financing and renewable energy consumption, with a coefficient of 0.07 for gf. Furthermore, the coefficient of green financing is significantly positive solely in the wind energy model, indicating its effectiveness in promoting renewable energy consumption and facilitating the low-carbon energy transition in developing countries, particularly in advancing wind energy usage. This preliminary finding supports hypothesis ***H1***.

Table 2 Effects of green financing on low-carbon energy transition, FE estimates

Dependent variable:	rc	bc	hc	sc	wc
Variables	(1)	(2)	(3)	(4)	(5)
gf	0.070*	0.005	0.030	0.008	0.020*
	(0.040)	(0.004)	(0.022)	(0.006)	(0.011)
eco	0.167***	– 0.001	0.089***	0.022***	0.042***
	(0.016)	(0.002)	(0.009)	(0.002)	(0.004)
urb	68.48***	0.678	39.65***	7.012***	15.60***
	(5.978)	(0.666)	(3.348)	(0.955)	(1.598)
ind	– 6.367**	– 0.778	– 3.284**	– 0.958**	– 1.543**
	(2.621)	(0.519)	(1.468)	(0.418)	(0.701)
pop	– 0.297	– 0.301***	0.009	0.049	– 0.118
	(0.730)	(0.098)	(0.409)	(0.116)	(0.195)
fdi	4.948*	1.885***	2.213	0.637	1.240*
	(2.796)	(0.719)	(1.566)	(0.446)	(0.748)
coal	– 100.1***	2.197	– 50.80***	– 15.11***	– 28.15***
	(22.19)	(1.887)	(12.43)	(3.546)	(5.932)
read	– 344.0	– 89.44***	34.95	– 76.39*	– 167.1**
	(258.7)	(24.52)	(144.9)	(41.16)	(69.18)
Constant	– 4,004***	49.90	– 2,374***	– 424.2***	– 907.8***
	(351.8)	(45.89)	(197.1)	(55.93)	(94.07)
Year fixed	Yes	Yes	Yes	Yes	Yes
Country fixed	Yes	Yes	Yes	Yes	Yes
Obs.	568	303	568	559	568
Number of countries	32	18	32	32	32
R-squared	0.495	0.285	0.480	0.379	0.452

This table presents the estimates of green financing's impact on the consumption of renewable energy and different energy types, as shown in columns (1) through (5), respectively. Specifically, the variables, rc, bc, hc, sc and wc refer to the consumption of renewable energy (TWh), biomass energy (TWh), hydro energy (TWh), solar energy (TWh), and wind energy (TWh), respectively. In all models, year and individual (country) effects are fixed to control for the effects of confounding factors. ***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively

4.1.2 IV Estimates

Considering the previously mentioned endogeneity concerns, we conduct IV estimation using 2SLS, employing the squared mean value of access to green finance for other countries in the same year ($mean\_gf2$) as the instrument. The results are presented in Table 3. We observe a coefficient of 0.088 for green finance (gf), slightly larger than the previously estimated 0.07, suggesting that each additional million dollars of green finance could result in an average increase of 88 GWh in renewable energy consumption in developing countries. Considering China, the largest energy producer and consumer, and based on the historical growth rate (9.83%), we anticipate China to receive \$164.2 million in green financing by 2025. This funding is anticipated to drive 14.45 TWh of renewable energy consumption in China, constituting 4.4‰ of China's 2025 renewable energy generation target[9]

[9] According to the 14th Five-Year Plan for Renewable Energy Development, China's annual renewable energy generation is expected to reach about 3.3 trillion kWh in 2025.

Table 3 Effects of green financing on low-carbon energy transition, IV estimates

Dependent variable:	rc	bc	hc	sc	wc
Variables	(1)	(2)	(3)	(4)	(5)
gf	0.088**	0.004	0.045*	0.007	0.024**
	(0.043)	(0.004)	(0.024)	(0.007)	(0.012)
eco	0.167***	– 0.001	0.089***	0.022***	0.042***
	(0.016)	(0.002)	(0.009)	(0.002)	(0.004)
urb	68.45***	0.690	39.63***	7.014***	15.59***
	(5.979)	(0.667)	(3.350)	(0.955)	(1.599)
ind	– 6.392**	– 0.768	– 3.305**	– 0.957**	– 1.548**
	(2.622)	(0.520)	(1.469)	(0.418)	(0.701)
pop	– 0.304	– 0.298***	0.003	0.050	– 0.119
	(0.731)	(0.098)	(0.409)	(0.116)	(0.195)
fdi	4.876*	1.874***	2.153	0.640	1.225
	(2.797)	(0.719)	(1.567)	(0.446)	(0.748)
coal	– 100.0***	2.179	– 50.71***	– 15.12***	– 28.13***
	(22.19)	(1.888)	(12.43)	(3.546)	(5.933)
read	– 326.5	– 90.79***	49.60	– 77.25*	– 163.4**
	(259.3)	(24.64)	(145.3)	(41.25)	(69.34)
Constant	– 4,609***	– 4.011	– 2,735***	– 457.2***	– 1,027***
	(423.2)	(53.08)	(237.1)	(67.52)	(113.1)
Year Fixed	Yes	Yes	Yes	Yes	Yes
Country fixed	Yes	Yes	Yes	Yes	Yes
Obs.	568	303	568	559	568
Number of countries	32	18	32	32	32
R-squared	0.895	0.896	0.937	0.545	0.707
KP rk LM	478.9	250.1	478.9	471.3	478.9
P-value of KP rk LM	0	0	0	0	0
KP rk Wald F	2745	1229	2745	2697	2745
Stock-Yogo	16.38	16.38	16.38	16.38	16.38

This table presents the estimates of green financing's impact on the consumption of renewable energy and different energy types, as shown in columns (1) through (5), respectively. Specifically, the variables, re, be, he, se and we refer to the consumption of renewable energy (TWh), biomass energy (TWh), hydro energy (TWh), solar energy (TWh), and wind energy (TWh), respectively. In all models, year and individual (country) effects are fixed to control for the effects of confounding factors. Kleibergen-Paap rk LM statistic is used to test whether the instrumental variable can be identified. Kleibergen-Paap rk Wald F-statistic is used to test whether the instrumental variable is a weak instrument. The Stock-Yogo statistic refers to the critical value at the 10% level provided by Stock and Yogo (2005) for identifying weakly instrumented variables. ***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively

(3.5‰ with fixed effects). Despite appearing modest, this impact holds significance. Aligning with China's 14th Five-Year Plan for Renewable Energy Development, green financing initiatives aim to foster international technological innovation and cooperation in renewable energy, standardized systems, as well as cooperation and exchange platforms, fostering long-term low-carbon transition development. Our study reinforces the positive impact of international green financing in promoting low-carbon energy transition in developing countries, affirming hypothesis ***H1***. However, it is crucial to acknowledge the significant variation in green financing across beneficiary countries and the susceptibility of future flows to various external uncertainties.

Additionally, the IV estimation results demonstrate that green financing effectively directs investments towards hydro (0.045) and wind (0.024) energy consumption. Similar findings are supported by a study focused on the Chinese context (Liu et al. 2023b). Green financing plays a direct role in providing financial support for renewable energy projects, thereby facilitating the implementation of government-led renewable energy development initiatives (Liu et al. 2023b). The positive impact observed in hydro energy consumption may be attributed to its inherent flexibility, storage advantages, and economies of scale (Liu and He 2023). Wind energy, characterized by its capital-intensive nature (Best 2017), tends to attract significant support. By reducing reliance on fossil fuels, wind energy contributes to improved air quality and climate mitigation efforts (Millstein et al. 2017). Notably, between 2007 and 2015, wind power generation in the United States led to a 26% reduction in sulfur dioxide (SO_2) and a 17% reduction in nitrogen oxides (NO_x), resulting in approximately $54 billion in air quality and public health benefits (Millstein et al. 2017).

4.2 Robustness Tests

To verify the accuracy of the previous estimation results, we conduct robustness tests employing two alternative strategies: replacing the measurement approaches for both low-carbon energy transition and green financing.

4.2.1 Evaluating Low-carbon Energy Transition via Renewable Electricity use

The electricity sector typically represents the majority of energy demand and serves as the cornerstone for advancing the energy transition (Bogdanov et al. 2021). Therefore, we opt to gauge the low-carbon energy transition using renewable electricity consumption, encompassing electricity consumption from various energy sources, similar to Liu et al. (2023a). We utilize IV estimation with fixed year and individual effects, and the outcomes are displayed in Table 4. The findings indicate that green financing fosters the expansion of renewable electricity (with a coefficient of 0.033 and significance at the 5% level), and this favorable impact extends to hydropower, wind, and biomass generation. Specifically, an additional $1 million in green financing results in a 33 GWh increase in renewable electricity. This discovery suggests that the influx of green finance can propel the energy transition in the power sector, affirming the resilience of the benchmark regression results.

4.2.2 Evaluating Green Financing via its GDP Share

In another robustness test, we assess the effect of financing by examining the share of green financing relative to GDP. This metric elucidates the significance of green financing within a country's economic framework. Employing the same estimation approach as the previous robustness test, the findings are presented in Table 5. The results indicate that an uptick in the share of green financing (as a percentage of GDP) effectively stimulates the expansion of renewable energy consumption, with a complementary increase observed in hydro and wind energy consumption. Specifically, hydro and wind energy are projected to contribute approximately half and a quarter, respectively, to the overall growth in renewable

Table 4 Robustness checks: effects of green financing on low-carbon energy transition (measured by renewable electricity consumption), IV estimates

Dependent variable:	re	be	he	se	we
Variables	(1)	(2)	(3)	(4)	(5)
gf	0.033**	0.003**	0.018*	0.003	0.009**
	(0.016)	(0.001)	(0.009)	(0.003)	(0.004)
eco	0.063***	0.004***	0.035***	0.008***	0.016***
	(0.006)	(0.000)	(0.003)	(0.001)	(0.002)
urb	25.63***	1.574***	15.36***	2.660***	5.882***
	(2.276)	(0.186)	(1.309)	(0.358)	(0.608)
ind	– 2.442**	– 0.201**	– 1.321**	– 0.364**	– 0.592**
	(0.998)	(0.080)	(0.574)	(0.157)	(0.266)
pop	– 0.063	– 0.017	– 0.024	0.023	– 0.043
	(0.278)	(0.022)	(0.160)	(0.044)	(0.074)
fdi	1.794*	0.191**	0.911	0.236	0.466
	(1.065)	(0.085)	(0.612)	(0.168)	(0.284)
coal	– 38.73***	– 2.159***	– 20.22***	– 5.725***	– 10.66***
	(8.449)	(0.671)	(4.858)	(1.330)	(2.255)
read	– 110.1	– 20.96***	1.551	– 27.92*	– 62.57**
	(98.73)	(7.832)	(56.77)	(15.548)	(26.36)
Constant	– 1,729***	– 101.2***	– 1,056***	– 173.5***	– 387.0***
	(161.1)	(13.12)	(92.64)	(25.37)	(43.01)
Year fixed	Yes	Yes	Yes	Yes	Yes
Country fixed	Yes	Yes	Yes	Yes	Yes
Obs.	568	550	568	568	568
Number of countries	32	31	32	32	32
R-squared	0.883	0.772	0.930	0.541	0.702
KP rk LM	478.9	460.2	478.9	478.9	478.9
P-value of KP rk LM	0	0	0	0	0
KP rk Wald F	2745	2532	2745	2745	2745
Stock-Yogo	16.38	16.38	16.38	16.38	16.38

This table presents the estimates of green financing's impact on the consumption of renewable electricity and different types of electricity, as shown in columns (1) through (5), respectively. Specifically, the variables, re, be, he, se and we refer to the consumption of renewable electricity (TWh), biomass electricity (TWh), hydro electricity (TWh), solar electricity (TWh), and wind electricity (TWh), respectively. In all models, year and individual (country) effects are fixed to control for the effects of confounding factors. Kleibergen-Paap rk LM statistic is used to test whether the instrumental variable can be identified. Kleibergen-Paap rk Wald F-statistic is used to test whether the instrumental variable is a weak instrument. The Stock-Yogo statistic refers to the critical value at the 10% level provided by Stock and Yogo (2005) for identifying weakly instrumented variables. ***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 5 Robustness checks: effects of green financing (as a proportion of GDP) on low-carbon energy transition, IV estimates

Dependent variable:	rc	bc	hc	sc	wc
Variables	(1)	(2)	(3)	(4)	(5)
gfp	20.57**	0.819	10.52*	1.594	5.524**
	(10.28)	(0.930)	(5.747)	(1.616)	(2.747)
eco	0.168***	– 0.001	0.090***	0.022***	0.042***
	(0.016)	(0.002)	(0.009)	(0.003)	(0.004)
urb	68.97***	0.743	39.89***	7.051***	15.73***
	(6.077)	(0.671)	(3.396)	(0.959)	(1.623)
ind	– 6.569**	– 0.725	– 3.395**	– 0.971**	– 1.595**
	(2.667)	(0.523)	(1.491)	(0.420)	(0.712)
pop	– 0.235	– 0.280***	0.038	0.055	– 0.100
	(0.742)	(0.098)	(0.415)	(0.117)	(0.198)
fdi	5.127*	1.877**	2.281	0.660	1.292*
	(2.837)	(0.726)	(1.586)	(0.447)	(0.758)
coal	– 98.70***	2.351	– 50.04***	– 15.01***	– 27.78***
	(22.56)	(1.922)	(12.61)	(3.561)	(6.027)
read	– 383.3	– 94.24***	20.53	– 81.63**	– 178.6**
	(260.3)	(24.26)	(145.5)	(40.89)	(69.53)
Constant	– 4,623***	– 8.224	– 2,743***	– 458.1***	– 1,030***
	(430.0)	(53.43)	(240.3)	(67.75)	(114.9)
Year fixed	Yes	Yes	Yes	Yes	Yes
Country fixed	Yes	Yes	Yes	Yes	Yes
Obs.	568	303	568	559	568
Number of countries	32	18	32	32	32
R-squared	0.891	0.895	0.935	0.542	0.698
KP rk LM	174.9	76.78	174.9	172	174.9
P-value of KP rk LM	0	0	0	0	0
KP rk Wald F	227.3	88.25	227.3	223.2	227.3
Stock-Yogo	16.38	16.38	16.38	16.38	16.38

This table presents the estimates of the impact of green financing (as a share of GDP) on the consumption of renewable energy and different energy types, as shown in columns (1) through (5), respectively. Specifically, the variables, rc, bc, hc, sc and wc refer to the consumption of renewable energy (TWh), biomass energy (TWh), hydro energy (TWh), solar energy (TWh), and wind energy (TWh), respectively. In all models, year and individual (country) effects are fixed to control for the effects of confounding factors. Kleibergen-Paap rk LM statistic is used to test whether the instrumental variable can be identified. Kleibergen-Paap rk Wald F-statistic is used to test whether the instrumental variable is a weak instrument. The Stock-Yogo statistic refers to the critical value at the 10% level provided by Stock and Yogo (2005) for identifying weakly instrumented variables. ***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively energy consumption, mirroring the outcomes of the benchmark regression. Consequently, an escalation in the share of green financing plays a pivotal role in advancing the low-carbon energy transition, thereby reaffirming the robustness of the benchmark results.

4.3 Heterogeneity Tests

4.3.1 Income Heterogeneity

We conduct a comparative analysis to ascertain potential disparities in the influence of green financing across countries with varying income levels. The sample is categorized based on the World Bank's income classification, with countries having a GNI per capita of less than $4,465, as per the World Bank Atlas method, designated as low-income samples, and vice versa for high-income samples. The IV estimation results reveal a significant positive coefficient of green financing in low-income samples, whereas it is not significant in high-income samples (see Table 6). This suggests that green financing is more impactful in facilitating the low-carbon energy transition in low-income economies compared to their high-income counterparts. The underlying reason may lie in the ability of green finance inflows to address the financial deficit in low-income countries and regions, thereby exerting a substantial influence on transitioning to low-carbon energy systems. A staggering fact is that approximately 97% of sustainable fund assets are concentrated in developed regions (UNCTAD 2021). In contrast, higher-income economies primarily encounter constraints related to advanced knowledge and technological limitations. This discovery underscores the divergence in policy preferences among countries of varying income levels and underscores the importance of international cooperation in bolstering collaborative initiatives with low-income countries and offering technical support to bridge the transition gap.

4.3.2 Asymmetry

In addition, the impact of green finance on the low-carbon transition may exhibit nonlinearity, particularly due to variations in renewable energy transition progress among sample countries. To examine potential nonlinear effects, we employ the panel quantile regression technique to assess asymmetry in the impact of green finance on the low-carbon energy transition. Table 7 presents the estimation results at the 20th, 40th, 60th, and 80th quantiles. The results indicate a positive coefficient on green finance across all quantiles, statistically significant at the 1% level, with its magnitude tending to increase as the quantile rises. This suggests a gradual amplification of the effect of green financing as the low-carbon energy transition progresses, indicative of a nonlinear relationship. Economies with more advanced transitions often possess well-established renewable energy generation infrastructure, advanced energy storage technologies, and supportive policy environments, including renewable energy quotas and subsidies (Carley and Konisky 2020). These favorable infrastructural conditions likely enhance the effectiveness and efficiency of green finance inflows.

Table 6 Heterogeneity checks: effects of green financing on low-carbon energy transition in different income groups, IV estimates

Dependent variable: rc		
Variables	Low income	High income
	(1)	(2)
gf	0.050***	0.062
	(0.013)	(0.076)
eco	0.041***	0.155***
	(0.014)	(0.023)
urb	3.241	107.6***
	(2.251)	(9.198)
ind	– 3.265***	– 9.540**
	(1.239)	(3.867)
pop	0.449**	-4.582
	(0.221)	(4.520)
fdi	2.376	3.289
	(3.061)	(3.526)
coal	– 27.95***	– 108.4***
	(9.597)	(31.14)
read	– 83.39	– 1,125**
	(77.31)	(477.6)
Constant	– 202.2	– 10,521***
	(176.6)	(745.5)
Year fixed	Yes	Yes
Country fixed	Yes	Yes
Obs.	234	334
Number of countries	13	19
R-squared	0.909	0.913
KP rk LM	204.6	284.4
P-value of KP rk LM	0	0
KP rk Wald F	1365	1663
Stock-Yogo	16.38	16.38

This table presents the estimates of green financing's impact on renewable energy consumption for different income groups, as shown in columns (1) through (2), respectively. Specifically, rc refers to the consumption of renewable energy (TWh). The low-income and high-income groups are based on the World Bank income classification criteria. In all models, year and individual (country) effects are fixed to control for the effects of confounding factors. Kleibergen-Paap rk LM statistic is used to test whether the instrumental variable can be identified. Kleibergen-Paap rk Wald F-statistic is used to test whether the instrumental variable is a weak instrument. The Stock-Yogo statistic refers to the critical value at the 10% level provided by Stock and Yogo (2005) for identifying weakly instrumented variables. ***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively

5 Effect of Digital Economy on the nexus between Green Financing and low-carbon Energy Transition

The growth of digital economy has facilitated numerous international green financing initiatives (Akberdina et al. 2024). However, empirical evidence quantifying its impact remains scarce. Therefore, we delve deeper into the digital economy's role in driving the transition to renewable energy by examining its moderating effects on financing. Table 8 presents the IV estimates, elucidating its influence on renewable energy consumption and various

Table 7 Heterogeneity checks: effects of green financing on low-carbon energy transition at different quantile levels, quatile estimates

Dependent variable: rc				
Variables	20th	40th	60th	80th
	(1)	(2)	(3)	(4)
gf	0.025***	0.068***	0.196***	0.288***
	(0.003)	(0.007)	(0.006)	(0.025)
eco	0.000*	0.004***	0.003***	0.004***
	(0.000)	(0.001)	(0.000)	(0.001)
urb	– 0.195***	0.469***	0.432***	0.586***
	(0.029)	(0.030)	(0.058)	(0.075)
ind	0.222***	– 0.931***	– 0.815***	– 0.684***
	(0.067)	(0.038)	(0.036)	(0.111)
pop	– 0.024***	– 0.001	– 0.000	0.036***
	(0.005)	(0.003)	(0.003)	(0.005)
fdi	– 0.056	0.203***	0.141	– 0.131
	(0.038)	(0.052)	(0.102)	(0.284)
coal	1.792***	– 1.144	20.57***	183.6***
	(0.304)	(1.114)	(0.795)	(11.12)
read	55.77***	23.72***	99.04***	225.0***
	(2.550)	(7.606)	(6.935)	(8.379)
Year fixed	Yes	Yes	Yes	Yes
Country fixed	Yes	Yes	Yes	Yes
Obs.	568	568	568	568
Number of countries	32	32	32	32

This table presents the estimates of green financing's impact on renewable energy consumption at different quantile levels (including 20th, 40th, 60th, and 80th quantiles), as shown in columns (1) through (4), respectively. Specifically, rc refers to the consumption of renewable energy (TWh). The panel quantile regression technique is used. In all models, year and individual (country) effects are fixed to control for the effects of confounding factors. ***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively

energy types. Column (1) of the results demonstrates a positive facilitating effect of digital economy development on renewable energy consumption, a finding consistent with prior literature (Xu et al. 2022). Furthermore, it amplifies the positive impact of green financing on renewable energy consumption, as evidenced by significantly positive coefficients of the interaction terms between digital economy (de) and green financing (gf). This indicates a constructive moderating effect of the digital economy on the relationship between green financing and the low-carbon energy transition. Hypothesis ***H2*** is thus validated.

The results also demonstrate the moderating influence of the digital economy on various energy sources. Building upon the main regression findings, we observe that the digital economy contributes to the increase in hydro and wind energy consumption. This observation aligns with specific studies conducted in countries such as China (Zheng and Wong 2024). The promotion of technological innovation in hydro and wind energy by the digital economy could be an important channel (Yi et al. 2024). Therefore, the digital economy can facilitate the promotion of green financing on hydro and wind energy consumption, i.e., the positive moderating effect of digital economy still exists in hydro and wind energy models.

Table 8 Mechanism checks: effects of digital economy on the nexus between green financing and low-carbon energy transition, IV estimates

Dependent variable:	rc	bc	hc	sc	wc
Variables	(1)	(2)	(3)	(4)	(5)
gf	0.252**	0.013	0.169**	0.014	0.039**
	(0.118)	(0.011)	(0.086)	(0.010)	(0.019)
eco	− 0.014	0.001	− 0.011	− 0.000	− 0.001
	(0.012)	(0.001)	(0.009)	(0.001)	(0.002)
urb	− 3.391	0.590*	− 2.092	− 0.468**	− 0.980**
	(2.478)	(0.311)	(1.805)	(0.203)	(0.403)
ind	4.958	− 1.705***	4.031	0.415	1.221**
	(3.513)	(0.407)	(2.559)	(0.284)	(0.572)
pop	0.178	0.046	0.132	0.008	0.021
	(0.169)	(0.043)	(0.123)	(0.014)	(0.027)
fdi	− 8.502	0.612	− 6.926	− 0.415	− 1.221
	(7.004)	(1.579)	(5.102)	(0.566)	(1.140)
coal	103.1***	− 2.130	89.29***	2.013	9.086
	(36.38)	(2.870)	(26.50)	(2.952)	(5.922)
read	766.5	57.59	704.1*	24.12	86.97
	(528.6)	(47.70)	(385.0)	(42.66)	(86.05)
de	1,328***	13.96	948.6***	73.91***	179.3***
	(230.6)	(24.45)	(168.0)	(18.69)	(37.54)
*de*gf*	2.415***	0.106***	1.645***	0.144***	0.398***
	(0.461)	(0.039)	(0.336)	(0.037)	(0.075)
Constant	− 321.8	− 5.171	− 292.7	− 8.907	− 42.13
	(298.0)	(35.61)	(217.0)	(24.14)	(48.51)
Year fixed	Yes	Yes	Yes	Yes	Yes
Country fixed	Yes	Yes	Yes	Yes	Yes
Obs.	443	285	443	434	443
Number of countries	25	17	25	25	25
R-squared	0.256	0.216	0.250	0.184	0.238
KP rk LM	378.6	233.5	378.6	370.9	378.6
P-value of KP rk LM	0	0	0	0	0
KP rk Wald F	2438	1166	2438	2388	2438
Stock-Yogo	16.38	16.38	16.38	16.38	16.38

This table presents the moderating effects of digital economy on the relationship between green financing and renewable energy consumption as well as different energy types, as shown in columns (1) through (5), respectively. Specifically, the variables, rc, bc, hc, sc and wc refer to the consumption of renewable energy (TWh), biomass energy (TWh), hydro energy (TWh), solar energy (TWh), and wind energy (TWh), respectively. In all models, year and individual (country) effects are fixed to control for the effects of confounding factors. Kleibergen-Paap rk LM statistic is used to test whether the instrumental variable can be identified. Kleibergen-Paap rk Wald F-statistic is used to test whether the instrumental variable is a weak instrument. The Stock-Yogo statistic refers to the critical value at the 10% level provided by Stock and Yogo (2005) for identifying weakly instrumented variables. ***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively

On the one hand, the positive impact of digital economy on the low-carbon transition may arise from its benefits in digital infrastructure development, social impact, support, and digital trade. Initially, the advancement of the digital economy heavily relies on digital infrastructure (Luo et al. 2021). For instance, China is implementing policies to encourage increased investment in new infrastructure, encompassing 5G infrastructure, new energy charging stations, and big data centers (MIIT 2021). Sophisticated digital infrastructures, such as energy internet platforms (Lin and Huang 2023) and smart grid construction (Shahbaz et al. 2022), can offer superior dual detection, management, and optimization tools for clean energy projects (Chowdhury et al. 2022). Secondly, digital technology development fosters various forms of social networking interactions and digital telecommuting (Stermieri et al. 2023), gaining heightened recognition and acceptance among social groups. Extensive social engagement and raised awareness levels aid in steering the energy sector towards low-carbon avenues, such as users' endeavors to alter home energy consumption patterns (Torriti 2017). Moreover, the significance of digital trade in facilitating low-carbon energy transition warrants attention. Digital trade facilitates cross-border technological innovation and knowledge transfer. Firms can communicate internationally through digital channels, thereby accessing advanced environmental technologies, management expertise, and innovation models (Cui et al. 2022; Xiong and Luo 2023). Digital trade also fosters intergovernmental collaboration and standardization, thus diminishing barriers to clean energy projects.

On the other hand, the digital economy's role in optimizing the allocation of green financial resources confers a notable advantage in attracting green financing. Akberdina et al. (2024) observe that the integration of digital technologies in the environmental sector drives the growth of environmental finance in Russia, particularly in the energy sector, leading to significant investment inflows in new environmental technologies. Similarly, in a study by Liu and Zhu (2024), the beneficial effect of digital economy on green financing allocation is identified, enhancing the carbon efficiency improvement of green finance. The adoption of digital technologies, such as blockchain technology, aids in enhancing the security and traceability of financial transactions, reducing financing costs and risks (Li et al. 2024).

6 Conclusions and Policy Suggestions

6.1 Conclusions

This study empirically examines the impact of international green financing on the low-carbon energy transition in developing countries and identifies the moderating effect of the digital economy on their relationship. Overall, we emphasize the following findings: First, green financing effectively promotes the low-carbon energy transition in developing countries, particularly evident in its positive impact on hydro and wind energy consumption. Additionally, green financing catalyzes the transition in the power sector, corroborating the robustness of the results. Second, we observe income heterogeneity and nonlinear effects in the impact of green financing on the low-carbon energy transition. It notably facilitates the transition in low-income economies facing financing challenges compared to high-income counterparts. Moreover, its effectiveness increases progressively as the energy transition advances. Lastly, the digital economy significantly contributes to driving the low-carbon energy transition and enhances the role of green finance therein. These findings offer empirical evidence supporting international green financing and underscore the pivotal role of digital economy in advancing the low-carbon energy transition.

6.2 Policy Suggestions

According to the primary findings of our study, we offer policy insights for policymakers in the following areas.

To advance the global low-carbon energy transition, we recommend scaling up green financing for developing economies based on existing commitments. Investors should explore clean energy project investment opportunities in regions with limited financing, aiding their transition to a low-carbon model and contributing to global greenhouse gas emission reduction under the Clean Development Mechanism framework. Simultaneously, beneficiary countries must enhance green financing regulations, ensuring transparency, sustainability, and the establishment of clear standards and review mechanisms to mitigate "greenwashing" risks.

Optimizing the allocation of green financial resources among energy types is critical for investment efficiency. Investment decisions should consider resource endowments and expected returns. In regions with high energy poverty levels, supporting stable hydro energy may secure energy supplies. However, long-term low-carbon and sustainable development benefit from prioritizing investments in flexible wind and solar projects with higher future returns.

Promoting the digital economy is vital for driving the low-carbon energy transition. Government agencies play a pivotal role in guiding digital economy development. Governments should encourage investment in energy digital infrastructure, including smart grids, data management, and energy storage technologies, to enhance power system digitization. Additionally, they should foster digital technology innovation and application in energy project financing to bolster financing security and reduce costs. Educational initiatives to enhance digital literacy will facilitate the transition to a digital society, increasing public engagement in green financing and sustainable development.

6.3 Limitations and Potential Future Research Directions

The digital economy index we constructed provides empirical evidence for the existence of digital economy's impact on the relationship between green finance and the low-carbon energy transition. It does not quantify the economic consequences of digital economy development on energy transition in developing countries. Future research could explore the impact of digitalization more precisely. Additionally, due to data limitations, our study does not encompass all developing economies. Future research could explore datasets with broader coverage and improved representation.

Appendix A

Table A1 Results of the multicollinearity test

Variables	VIF	1/VIF
gf	1.06	0.9450
eco	1.86	0.5388
fdi	1.09	0.9167
pop	1.68	0.5950
urb	2.27	0.4401
ind	1.16	0.8589
coal	1.09	0.9216
read	1.29	0.7760
Mean VIF	1.44	

This table presents the results of multicollinearity test using the variance inflation factor (VIF). In empirical economics research, if VIF is greater than 10, it is considered that there is a serious covariance problem in the model

Table A2 Effects of green financing on low-carbon energy transition, OLS and RE estimates

Dependent variable: rc		
Variables	OLS	RE
	(1)	(2)
gf	0.310***	0.077*
	(0.115)	(0.043)
eco	0.016**	0.151***
	(0.008)	(0.016)
urb	– 0.621	33.15***
	(1.485)	(4.890)
ind	5.132*	– 8.337***
	(2.828)	(2.719)
pop	0.052	1.661***
	(0.043)	(0.462)
fdi	– 7.476**	5.499*
	(3.588)	(3.052)
coal	96.95***	– 118.2***
	(31.71)	(23.99)
read	1,875***	– 118.9
	(516.6)	(273.7)
Constant	– 753.5***	– 2,266***
	(220.8)	(343.6)
Year fixed	Yes	Yes
Country fixed	No	Yes
Obs.	568	568
R-squared	0.120	

This table presents the estimates of green financing' impact on the consumption of renewable energy. ***, **, and * refer to statistical significance at the 1%, 5%, and 10% levels, respectively

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

Declarations

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

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