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RESEARCH ARTICLE

The impact of energy security on environmental degradation: new evidence from developing countries

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Abstract

This study investigates the energy security and income roles in testing environmental Kuznets curve (EKC) for developing countries from 1990 to 2019. The panel quantile regression approaches are employed to examine the relationship between the variables, considering that income and energy security effects on carbon emissions may vary across distributions. Findings revealed that the EKC hypothesis was inconsistent at low and high quantiles when estimating energy availability, affordability, and acceptability. The validity of inverted U-shaped EKC is supported at high quantiles for energy affordability and accessibility in developing countries. However, given the energy accessibility and acceptability, the EKC hypothesis becomes invalid in developing countries. Notably, developing countries have yet to progress toward achieving energy security as a switch component to low carbon emissions. This study contributes to the literature by revealing the effect of availability, accessibility, affordability, and acceptability of energy security on carbon dioxide emissions (CO2). Thus, it suggests implications for improving environmental quality in developing countries by enhancing energy security. Diversifying energy sources with nuclear, renewable, and developing technologies reduces dependence risks on a single source while improving efficiency through technology and demand management lowers carbon emissions and strengthens energy security. Beyond energy security, this study emphasises sustainable urban planning to promote compact development, effective transportation, and green infrastructure to reduce energy use and improve environmental sustainability, ultimately reducing carbon emissions.

Keywords Energy security · Income · Developing countries · Quantile regression · Environmental Kuznets curve (EKC)

Introduction

In the twenty-first century, climate change is among the most significant global issues, which disrupts national economies and affects lives. Scientists concur that preventing the worst effects of climate change will require maintaining the global temperature below 2 °C. This degree should be above preindustrial levels since burning fossil fuels has already raised global temperatures by 1.1 °C (Hansen et al. 2013; Robinson and Shine 2018; Welsby et al. 2021). Concerning this issue, most countries have vowed to keep global warming below 2 °C. Optimising energy efficiency can be achieved through a cleaner energy transition, which reduces fossil fuel use and carbon dioxide (CO2) emissions (Fernando and Hor 2017; Solaymani 2019; Shah et al. 2023).

As a strategy for combating climate change, countries worldwide are taking steps towards energy security (Wang and Liu 2015; Gasser 2020). Countries can improve their energy security by decreasing their reliance on fossil fuels. This diversification often involves combining renewable energy sources such as solar, wind, hydropower, and geothermal. In addition, countries can lower their carbon footprint and promote a more sustainable energy future by utilising these rich and sustainable resources (Wang and Liu 2015; Gasser 2020). Bangladesh, for instance, is extremely responsive to the effects of climate change, such as increasing sea levels and an increased frequency of natural disasters. The country has actively invested in renewable energy to promote electricity to remote areas, particularly solar

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Highlights

• The energy security and income roles in testing Environmental Kuznets curve (EKC) are investigated for developing countries.
• This paper adds to the existing literature by examining the impact of the availability, accessibility, affordability, and acceptability (4As) of energy security on carbon emissions.
• It is believed that EKC is justified at high quantiles for energy affordability and accessibility in developing countries.

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household systems (Allard et al. 2018; Islam et al. 2014; Islam and Salma 2016). These initiatives increase the availability of electricity, reduce reliance on fossil fuels, improve energy security, and reduce emissions, particularly in remote and off-grid areas.

Climate change and energy security are considered major global concerns in the modern world. They necessitate lowering greenhouse gas (GHG) emissions while ensuring people access to ample, dependable, reasonably priced, modern, and clean energy supplies. Thus, considerable empirical work has been performed to analyse the link between climate change and energy security in developing (Bazilian et al. 2011; Shakya and Shrestha 2011; Toke and Vezirgiannidou 2013; Seriño 2022) and developed countries (Chalvatzis and Hooper 2009; Bang 2010; Le et al. 2022). These studies demonstrated that rapid industry expansion and fossil fuel consumptions (which produced GHG emissions) were the foremost causes of climate change. In addition, ensuring adequate, dependable, and environmentally friendly supplies could reduce emissions and address climate change concerns. Several studies have investigated the primary GHG emission based on the relationship between energy security and carbon emission (Chalvatzis and Hooper 2009; Bang 2010; Bazilian et al. 2011; Shakya and Shrestha 2011; Le et al. 2022). Energy security associated with energy efficiency and decarbonisation reduces fossil fuel demands and lowers CO2 levels in the atmosphere. Particularly, CO2 emissions reductions became noticeable in environmental outcomes, enhancing environmental quality and coherent with carbon neutrality goals. Energy security has often been depicted as a priority tool for environmental quality and a catalyst for significant economic development and prosperity. Typically, the energy security improvements positively affected the entire economy, with direct and indirect impacts on economic activity through GDP, employment, trade balances, and energy prices. For example, the European Commission estimated the energy efficiency improvement effects at various scenario levels by 2030 compared to the 2007 baseline year (IEA 2019). Each scenario positively affected GDP, ranging from a 0.1 to 2.0% increase (from least ambitious to higher energy efficiency scenario) (IEA 2019). Hence, energy security could hinder emission accelerations while enhancing the economic growth of a country.

Given the above discussion, this paper aims to extend the literature review on the relationships between environmental quality, economic growth, and energy security. For the past three decades, the environmental Kuznets curves (EKC) was focused on, which was considered a significant environmental economics research field that attracted numerous academics and researchers. Shittu et al. (2021) stand as the sole empirical research examining the relationship between energy security and environmental degradation, which measured energy security from the perspective of energy availability in 45 resource-rich Asian countries using two-stage least squares. The study revealed substantial evidence that energy security is negatively related to ecological footprint, reducing the environmental degradation in Asian countries, besides highlighting the non-existence of EKC patterns. However, not only did Shittu et al. (2021) focused solely on Asian countries, but they also measured energy security differently. Moreover, the study did not address developing countries' efforts to establish energy security to reduce emissions by restricting their analysis to Asian countries. Additionally, Shittu et al. (2021) study's approach to measuring energy security was based on the difference between electricity supply and demand, primarily addressing the energy availability dimension. The study offers valuable insight, but they do not provide a comprehensive understanding of the role of energy security on environmental emissions. This constraint might be explained by the focus on the 4As—availability, affordability, accessibility, and acceptability—that serve as a common initial approach in contemporary energy security studies. Thus, the discussion above raised the following questions: (1) how do the 4As of energy security impact the state of environmental emissions in developing countries? (2) Does EKC hold to the role of energy security in developing counties?

Considering the questions raised, this study examines the impact of 4As energy security on environmental degradation in developing countries since each dimension contributes to achieving the primary goal of lowering emissions and implementing sustainable energy practices. Accessibility encourages broader adoption of clean energy options, acceptability emphasises adopting environmentally friendly technologies, availability ensures a reliable energy supply for switching to cleaner sources, while affordability enables equitable access to sustainable energy solutions. Further, the present study also investigates the impact of energy security on the nature of EKC for developing countries. The EKC implies that environmental emissions decrease in high-income levels where economic growth observes environmental improvement. Energy security drives economic growth, as evidenced by Le and Nguyen (2019), Wei et al. (2020), Fu et al. (2021), as well as Khan et al. (2021). Given these findings, it is imperative to determine whether energy security is a significant variable impacting the dynamics of the EKC. By exploring this relationship, this study will advance knowledge of how developing countries' energy security, economic growth, and environmental emissions interact.

The remainder of this research is structured as follows. Firstly, the literature review is presented. Secondly, the empirical model and data description discussions are reported in the "Data and methodology" section. Thirdly, the empirical findings and their corresponding discussions are presented. The final section discusses the conclusion and the potential policy implications.

Literature review

The literature review section in the study is divided into two sections as follows:

(a) studies on how energy security affects environmental quality;
(b) specific literature since only several studies were studying the EKC hypothesis.

Energy security and environmental quality nexus studies

Several literatures on the nexus between energy security and the environment were observed. Studies done by Bauen (2006), Leiby (2007), Dowling and Russ (2012), Anwar (2016), Lin and Raza (2020), He et al. (2020), Sun et al. (2021), and Shittu et al. (2021) focused on the benefits of energy security leading to emission reduction. Meanwhile, the study by Leiby (2007) examined the impact of reduced energy imports on environmental emissions from 2005 to 2050 for the USA, which estimated roughly the marginal social benefits from a decline in US oil imports. Additionally, this study used savings and decreased fuel import costs as rough indicators for improved energy security. Hence, the study discovered that an oil import decrease could produce marginal economic benefits. Similarly, Anwar (2016) considered the energy security issues under energy import reduction targets for Pakistan by analysing the reduced energy import effects on environmental emissions. This study analysed how decreased reliance on energy imports improved environmental quality and increased energy security of Pakistan.

In another study, Fu et al. (2021) examined the energy security role using fuzzy-TOPSIS, which corresponded to the emission reduction dilemma and economic growth of the ten best-performing countries. The study discovered that energy production was crucial, with a significant CO2 amount released through coal and oil. Furthermore, higher energy efficiency and renewable energy promotion led to less dependence on oil consumption, which created new pathways in lowering CO2 emissions and developing a green economy. From 2010 to 2050, Kumar (2016) evaluated the renewable energy of Indonesia and Thailand for energy security and carbon emission reduction. The LEAP energy model in the simulation revealed that a significant portion of renewable electricity in the energy mix decreased CO2 emissions in Thailand and Indonesia. Particularly, the share of renewable energy in the 2050 energy mix was projected to be 40% and 39% for Indonesia and Thailand, respectively. Hence, these projections could result in 81% (Indonesia) and 88% (Thailand) carbon emission reductions. Using the current wind and solar energy project invested by China, Gu and Zhou (2020) demonstrated the effect of renewable energy projects on the Belt and Road Initiative (BRI) emission reduction of China and their corresponding benefits for BRI-related countries. The study discovered that supporting renewable energy projects in China (through investment and development) could assist BRI-related countries in promoting the development of low-carbon energy systems, combating climate change and achieving sustainable development.

Lin and Raza (2020) used scenario analysis to study Pakistan's energy security indicators and carbon emissions. Several scenarios were examined to assess the changes in carbon emissions, and each showed a decrease in emissions. The use of cleaner energy sources and technological developments contributed to this reduction. Recently, Shittu et al. (2021) conducted an empirical study from 1990 to 2018 for Asian countries using a two-stage least square estimator to examine the role of energy security on ecological footprint. The ecological footprint measure for environmental degradation and the energy security measure, calculated as the sum of energy supply minus energy demand, showed a negative relationship between energy security and ecological footprint, indicating that countries must have secure energy supplies to mitigate environmental degradation. When a country has a stable supply of solar, wind, hydro, and geothermal power, it can adopt cleaner, more sustainable energy to replace fossil fuels and lower greenhouse gas emissions.

In summary, Bauen (2006), Dowling and Russ (2012), Kumar (2016), Leiby (2007), Anwar (2016), Lin and Raza (2020), He et al. (2020), Gu and Zhou (2020), Fu et al. (2021), and others predominantly relied on alternative methods including scenario, theoretical frameworks, simulations, and mathematical approach (Table 1). These methods analysed hypothetical scenarios, develop models, and make assumptions instead of directly analysing data from the real world. While these techniques have offered insightful information on the subject, very likely that they do not fully represent the complexity and variety of the real-world dynamics between energy security and carbon emissions. In addition, the 4As of energy security as influences on carbon emissions have not been extensively explored in previous studies despite their significance. The earlier studies employed a broader definition of energy security and often used renewable energy as an indicator. Renewable energy is a crucial component of energy security, but it overlooks the availability, affordability,

Table 1 Summary of energy security and environmental quality nexus studies

Authors	Time period	Country	Methods	Results	Limitations
Bauen (2006)	-	Global	-	Emission reductions result from improving energy security.	a) None of the studies applies the 4As of energy security. b) Lack of empirical validation using real word data
Dowling and Russ (2012)	-	Asia	Simulation model POLES (prospective outlook for the long-term energy system	Lower energy prices support the emission reduction effort	
Kumar (2016)	-	Indonesia and Thailand	LEAP (long-range energy alternatives planning system) model (scenario analysis)	Renewable electricity in the energy mixes decreased CO_2 emissions	
Leiby (2007)	2005 to 2050	United States	Marginal cost and benefit analysis (mathematical approach)	Marginal benefit of energy security is lower greenhouse gas emissions by reducing US oil imports.	
Anwar (2016)	2005–2050	Pakistan	Integrated energy system model (simulation analysis)	Energy security decreases gas emissions by reducing energy imports	
Lin and Raza (2020)	2012–2040	Pakistan	MARKAL framework (scenario analysis)	Energy security lessens carbon emission	
He et al. (2020)	-	Pakistan	Linear programming model	Transitioning to renewable energy sources, such as wind-generated power, improves energy security and reduces emissions.	
Gu and Zhou (2020)	-	China	Comparison of renewable energy projects	Renewable energy investment initiatives increase energy security while lowering carbon emissions.	
Fu et al. (2021)	2018	Denmark, Switzerland, Sweden, the Netherlands, UK, Slovenia, Germany, New Zealand, Norway, and France	Fuzzy-TOPSIS method (mathematical approach)	High energy efficiency reduces emission	
Sun et al. (2021)	1990–2018	Asia	Two-stage least square estimator	Energy security reduces the degradation of the environment	

acceptability, and accessibility dimensions of energy security, which may influence environmental emissions.

Studies investigating of the EKC hypothesis

Over the past few years, the environmental Kuznets curve (EKC) has been extensively studied in the context of economic development and environmental degradation. Grossman and Krueger (1991) pioneered an inverted U-shaped relation design based on income level and environmental degradation degree. In addition, income and income squared impacted degradation positively and negatively, respectively. In the early stage of economic growth, environmental degradation could rise with income until reaching a turning point. After this turning point, an increase in income could contribute to environmental improvement.

Following the work of Grossman and Krueger (1991), the EKC hypothesis using various sets of samples and methods was examined in numerous empirical studies (Saboori et al. 2016; Dong et al. 2018; Abumunshar et al. 2020; Ahmad et al. 2021; Fatima et al. 2021; Shittu et al. 2021; Awan et al. 2023). Nonetheless, several studies provided contradictory results (Halkos and Polemis 2017; Destek and Sinha 2020; Ntarmah et al. 2021; Zeraibi et al. 2022; Djellouli et al. 2022). Several studies also demonstrated the non-existence of EKC, indicated by either U-shaped (Begum et al. 2015; Destek and Sinha 2020), N-shaped (Halkos and Polemis 2017; Zeraibi et al. 2022), or monotonic-shaped (Djellouli et al. 2022; Mensah et al. 2021) relationship between environmental degradation and economic growth.

Recently, researchers have used a different method to investigate whether the EKC hypothesis is true by considering more factors in the relationship between income and environmental degradation. For example, Jebli et al. (2016) studied how the EKC hypothesis applied to renewable and non-renewable energy consumption and trade in OECD countries. The findings successfully confirmed the inverted U-shaped EKC hypothesis: higher renewable energy decreased carbon emissions while lower non-renewable energy increased carbon emissions. Meanwhile, Sarkodie and Ozturk (2020) investigated the EKC validity for Kenya which included energy use and urban population using ARDL, SIMPLS regression, and U-test techniques. For Kenya, the estimation result confirmed an inverted U-shaped curve, depicting how urbanisation and rising energy consumption could worsen CO2 emissions. Eren (2022) investigated the linear and nonlinear relationships between democracy, income, and emissions for 72 countries between 1993 and 2019 using a panel quantile regression approach. The study produced an inverted U-shaped relationship between income and emission for both low- and medium-emission countries, supporting the validity of the EKC hypothesis.

The results in the following studies contradict those discussed above. Zilio and Recalde (2011) utilised panel data for 21 Latin American and Caribbean countries, covering 1970 to 2007. The study implied that the estimation results do not support the idea that the variables have a long-term relationship, which was against the EKC. The ARDL bounds testing approach and dynamic OLS were studied by Begum et al. (2015) to investigate the dynamic effects of income, energy consumption, and population growth on CO2 emissions in Malaysia. Their findings demonstrated a negative and significant relationship between GDP and CO2 emissions, with carbon emissions declining as GDP increased. In addition, a positive correlation between GDP in quadratic form and carbon emissions was observed. Consequently, Malaysia acquired a U-shaped curve opposite to EKC, concluding that the EKC theory was invalid for this country. Alternatively, Djellouli et al. (2022) discovered that the EKC does not hold for a sample of 20 African nations between 2000 and 2015 using panel autoregressive distributed lag (panel ARDL). This observation suggested that pollution levels were rising along with economic growth, which was against the EKC hypothesis and in line with the findings of He et al. (2021), Zeraibi et al. (2022), Djellouli et al. (2022), and Xue et al. (2022).

Given the above literature, most studies considered the EKC hypothesis in the presence of energy consumption, renewable and non-renewable energy, urbanisation, and population growth, while others invalidated an EKC relationship. A summary of research literature review in Table 2 attests that no study on the linkage between energy security and carbon emissions within the context of the EKC hypothesis, except for Shittu et al. (2021). According to Shittu et al. (2021), Asian countries do not exhibit environmental Kuznets curve (EKC) patterns when there is energy security, indicating that the relationship between environmental degradation and economic growth in those countries does not exhibit the inverted U-shaped pattern often associated with the EKC theory. The non-existence of EKC might be influenced by the traditional regression approach of two-stage least squares, which deliver the mean impacts of energy security on the entire conditional distribution of the environmental emissions. This regression approach assumes that energy security variables have the same influence across the distribution of environmental emissions, thus hindering the identification of potential variations in how energy security may affect environmental emissions.

Research gap

Based on the research inadequacies of prior studies, this study will considerably contribute to the body of literature in two ways.

Table 2 Summary of studies of the EKC hypothesis

Author(s)	Country	Approach	Variables	Period	EKC exist
Saboori et al. (2016)	Malaysia	ARDL	Energy consumption, urbanisation, foreign trade, carbon dioxide emissions, income	1980–2008	Yes
Dong et al. (2018)	China	ARDL (structural breaks)	Carbon dioxide emissions, income, renewable energy consumption, natural gas consumption	1965–2016	Yes
Abumunshar et al. (2020)	Turkey	ARDL (Bootstrap)	Carbon dioxide emissions, income, non-renewable energy consumption, renewable energy consumption, crude oil prices	1985–2015	Yes
Ahmad et al. (2021)	11 developing countries.	PMG and FMOLS estimator	Carbon dioxide emissions, income, electricity consumption	1992–2014	Yes (Brazil, China, India, Malaysia, the Russian Federation, Thailand and Turkey) No (Mexico, Philippines, Indonesia and South Africa)
Fatima et al. (2021)	High emitting countries	Cointegration, generalised method of moments (GMM), causality	Carbon dioxide emissions, income, non-renewable energy consumption, renewable energy consumption	1980 to 2014	yes
Zeraibi et al. (2022)	China	ARDL	Carbon dioxide emissions, income, fiscal and monetary policies	1980 to 2018	No
Shittu et al. (2021)	Asia	Two-stage least square	Ecological footprint, natural resource rent, environmental performance index, energy security, income	1990 to 2018	No
Halkos and Polemis (2017)	OECD	GMM	Carbon dioxide emissions, income, financial development	1970–2014	No
Destek and Sinha (2020)	OECD	FMOLS and DOLS	Carbon dioxide emissions, income, renewable energy consumption, non-renewable energy consumption, trade openness	1980 to 2014	No
Ntarmah et al. (2021)	Sub-Saharan Africa	Panel vector autoregressive	Carbon dioxide emissions, income, credit supply, renewable energy consumption, population growth	1990–2018	Yes (East African sub-region) No (Central, Southern and West African)
Djellouli et al. (2022)	African countries	ARDL	carbon dioxide emissions, income, renewable energy consumption, non-renewable energy consumption, Foreign direct investment	2000–2015	No

Table 2 (continued)

Author(s)	Country	Approach	Variables	Period	EKC exist
Begum et al. (2015)	Malaysia	DOLS	Carbon dioxide emissions, income, energy consumption, population growth	1980 to 2009	No
Mensah et al. (2021)	Ghana	ARDL	Carbon dioxide emissions, income, natural resource rent, import, export, urbanisation	1976–2017	No
Sarkodie and Ozturk (2020)	Kenya	ARDL, SIMPLS regression and U test	Carbon dioxide emissions, income, electricity production, energy imports, energy consumption, agricultural land, industry value added, urban population	1971 to 2013	Yes
Eren (2022)	72 countries	Panel quantile regression method	Carbon dioxide emissions, income, political rights, population size, primary energy consumption, trade	1993 to 2019	Yes (low- and medium-emission countries) No (high-emission countries
Zilio and Recalde (2011)	Latin America and the Caribbean	cointegration	income, total primary energy supply	1970–2007	No
Awan et al. (2023)	China	Quantile method	Carbon dioxide emissions, income, hydropower generation, trade, urbanisation	1971 to 2017	Yes
Awan et al. (2022a)	10 emerging countries	Quantile method	Carbon dioxide emissions, income, renewable energy, internet use, foreign direct investment	1996–2015	Yes
Awan et al. (2022b)	107 countries	Quantile method	Energy efficiency, CO2 emission, income	1996 to 2014	Yes
Awan et al. (2022c)	Malaysia	Quantile method	CO2 emission, income, urbanisation	1965 to 2018	No

(i) The 4As of energy security have received less attention in past studies, which frequently employed energy availability or renewable energy as indicators for energy security. Despite having a considerable impact on carbon emissions, these dimensions of energy security have not been analysed in prior studies. This study offers a more comprehensive understanding of the linkage between energy security and environmental emissions by including the 4As in the analysis.

(ii) This study contributes significantly by investigating the relationship between energy security and carbon emissions within the context of the environmental Kuznets curve (EKC) hypothesis. Except for Shittu et al. (2021), earlier studies have comprehensively studied the EKC theory using diverse variables. This study fills the gap by employing panel quantile regression, which allows for a more thorough analysis by considering potential variations in the impact of energy security on emissions across different quantile ranges. Thus, in the framework of the EKC hypothesis, this methodology enables a more thorough investigation of the role of energy security in emissions.

Data and methodology

Data description

This study focused on the energy security effect of carbon emissions for selected developing countries. Based on the data availability, 112 developing countries were included. Since the period under consideration was tied to energy security measures, the annual sample data from 1990 to 2019 was selected. In EKC literature, the CO2 emissions per capita (in tonnes) were the main contributor to global warming and commonly used as a pollutant indicator. Thus, CO2 emissions per capita were chosen as the dependent variable for this current study. The key independent variable for testing the EKC hypothesis was the GDP per capita (constant 2010 US dollars), employed as an economic growth measure.

This study utilised the 4As of energy security. In this context, the primary energy production/population (kg/person) (quadrillion btu) was utilised as an energy availability indicator, access to electricity (% of population) as an accessibility indicator, consumption of renewable energy (% of total final energy consumption) as an acceptability indicator, and primary energy consumption (quadrillion btu) as an energy affordability indicator. The World Development Indicators (WDI) database of the World Bank and the International Energy Agency's data (IEA) and statistics were used to extract the independent and dependent variables' data. Table 3 tabulates the variable definitions and data sources.

Table 4 provides the descriptive statistical analysis. All the variable distributions were skewed, with the kurtosis values illustrating a longer tail for each variable. Additionally, the kurtosis values depicted a more concentrated contribution than what would be expected from a distribution with a normal shape. The unconditional distribution was not normal, as indicated by the Jarque-Bera statistical test, which also strongly rejected the normality hypothesis for all variables. Consequently, quantile regression was employed as a more efficient estimation method as OLS regression approach may demonstrate biased results (Koenker 2004; Salman et al. 2019).

Empirical model

Based on Grossman and Krueger (1991), Zeraibi et al. (2022), Shittu et al. (2021), and Qashou et al. (2022), the

Table 3 Summary of the variable descriptions and data sources

Variable	Description	Source
GDP	Real GDP per capita (constant 2010 USD)	World Bank (2022)
CO2	CO2 emissions per capita in tonnes	
Energy security (accessibility, ESACC)	Access to electricity (% of population)	
Energy security (acceptability, ESACCE)	Consumption of renewable energy (% of total final energy consumption)	
Energy security (availability, ESAVA)	Primary energy production/population (kg/person) (quadrillion btu)	World Bank (2022) and International Energy Agency's data (IEA)
Energy security (affordability, ESAFF)	Primary energy consumption (quadrillion btu)	World Bank (2022) and International Energy Agency's data (IEA)

Table 4 Summary of descriptive statistics

Variable	*CO2*	*GDP*	*ESACC*	*ESACCE*	*ESAVA*	*ESAFF*
Mean	0.9159	8.6399	2.6496	1.2882	1.2660	4.3678
Std. dev	1.3539	1.0357	0.4896	1.8995	0.9270	1.4397
Min	3.6891	5.3182	6.3399	1.1182	2.3452	0.8459
Median	1.2131	8.5070	3.0855	0.9226	0.6808	4.6031
Max	9.9305	11.6299	4.5884	4.8188	5.0228	4.6051
Skewness	– 0.6595	– 0.1594	– 0.4450	– 0.6116	– 2.8735	– 2.7659
Kurtosis	3.0097	2.1564	5.7651	3.6619	2.1994	3.5315
Jarque–Bera	196.65***	93.336***	55.390***	27.452***	35.75***	85.885

*** refers to statistical significance at the 1% level

empirical model proposed is based after the framework of the EKC hypothesis as follows:

$$CO2_{it} = f\left(GDP_{it}^{\beta 1}, GDP_{it}^{2\ \beta 2}\right) \tag{1}$$

In Eq. (1), the level of CO2 emissions was hypothesised to be significantly influenced by energy security and was incorporated into the EKC framework. Hence, this study uses the 4As of energy security to analyse the relationship between carbon emissions and energy security. The relationship between carbon emissions and the 4As of energy security is indicated by the following model:

Model 1

$$CO2_{it} = f\left(GDP_{it}^{\beta 1}, GDP_{it}^{2\ \beta 2}, ESAVA_{it}^{\beta 3}\right) \tag{2}$$

In the log-linear form, Eq. (2) is expressed as follows:

$$LCO2_{it} = \beta_0 + \beta_1 LGDP_{it} + \beta_2 LGDP^2{}_{it} + \beta_3 LESAVA_{it} + \varepsilon_{it} \tag{3}$$

Model 2

$$CO2_{it} = f\left(GDP_{it}^{\beta 1}, GDP_{it}^{2\ \beta 2}, ESACC_{it}^{\beta 3}\right) \tag{4}$$

In the log-linear form, Eq. (4) is expressed as follows:

$$LCO2_{it} = \beta_0 + \beta_1 LGDP_{it} + \beta_2 LGDP^2{}_{it} + \beta_3 LESACC_{it} + \varepsilon_{it} \tag{5}$$

Model 3

$$CO2_{it} = f\left(GDP_{it}^{\beta 1}, GDP_{it}^{2\ \beta 2}, ESACCE_{it}^{\beta 3}\right) \tag{6}$$

In the log-linear form, Eq. (6) is expressed as follows:

$$LCO2_{it} = \beta_0 + \beta_1 LGDP_{it} + \beta_2 LGDP^2{}_{it} + \beta_3 LESACCE_{it} + \varepsilon_{it} \tag{7}$$

Model 4

$$CO2_{it} = f\left(GDP_{it}^{\beta 1}, GDP_{it}^{2\ \beta 2}, ESAFF_{it}^{\beta 3}\right) \tag{8}$$

In the log-linear form, Eq. (8) is expressed as follows:

$$LCO2_{it} = \beta_0 + \beta_1 LGDP_{it} + \beta_2 LGDP^2{}_{it} + \beta_3 LESAFF_{it} + \varepsilon_{it} \tag{9}$$

From Eq. (2) until Eq. (9), $LCO2_{it}$ is the level of CO2 emissions in natural logarithmic form in country i at time t, $LGDP_{it}$ and $LGDP^2{}_{it}$ are the income level and the squared income level in the natural logarithmic form in county $\underline{i}$ at time t, respectively, while $LESAVA_{it}$, $LESACC_{it}$, $LESACCE_{it}$, and $LESAFF_{it}$ are the level of energy availability, accessibility, acceptability, and affordability in country i at time t, respectively. The error term is represented by ε_{it}.

The graphical illustration of the EKC hypothesis was shaped by the β_1 and β_2 coefficients, which depicted the association between carbon emissions and income. The EKC hypothesis was valid when these coefficients were $\beta_1 < 0$ and $\beta_2 > 0$, indicating a quadratic inverted U-shaped relationship. When the coefficients supported the EKC hypothesis β_1 and β_2, the income turning point became $-\left[\frac{\beta_1}{2\beta_2}\right]$.

The statistical distribution of data demonstrated that the unconditional distribution was not normal. This demonstration indicated the biasing of the conventional regression approach concentrating on the mean impacts and even failed to reveal significant correlations (Binder and Coad 2011). In this study, the panel quantile regression approach was utilised to assess the impact of the 4As of energy security on carbon emissions within the context of the EKC hypothesis. The quantile regressions examined the different points on the conditional distribution of the dependent variables. Thus, a more comprehensive picture of the relationship between the variables could be provided (Cade and Noon 2003; Eren 2022). Additionally, unlike the OLS, the panel quantile technique could capture the heterogeneous structure of different income groups.

The conditional distribution of the dependent variable was divided into quantiles in quantile regressions, where the 50th quantile represents the median (Allard et al. 2018). Quantile regressions were more resistant to outliers than other estimation methods which uses mean. For variables like CO2 emissions and economic development, Hübler (2017) claimed that there were significant differences between the median and mean. Therefore, quantile regression is an interesting method for testing the EKC hypothesis as it allows for estimation of various slopes for different quantiles. Given that, the conditional quantile of Y_i given x_i is expressed as follows:

$$Q_{yit} = \left(\tau|x_{it}\right) = x_{it}^{\tau}\beta_{\tau} \tag{10}$$

where $Q_{yit} = (\tau|x_{it})$ represents the τ^{th} quantile of the dependent variable, x_{it}^{τ} is the vector of explanatory variables for country i at year t for quantile τ, and β_{τ} denotes the slopes of the explanatory variables for quantile τ (Allard et al. 2018). Taking Eq. (10) into consideration, Eqs. (11) to (14) were formulated to analyse the impact of the 4As of energy security on carbon emissions at quantile levels, as follows:

Model 1

$$Q_{\tau}\left(LCO2_{it}\right) = \beta_{\tau} + \beta_{1\tau}LGDP_{it} + \beta_{2\tau}LGDP^{2}{}_{it} + \beta_{3\tau}LESAVA_{it} + \varepsilon_{it} \tag{11}$$

Model 2

$$Q_{\tau}\left(LCO2_{it}\right) = \beta_{\tau} + \beta_{1\tau}LGDP_{it} + \beta_{2\tau}LGDP^{2}{}_{it} + \beta_{3\tau}LESACC_{it} + \varepsilon_{it} \tag{12}$$

Model 3

$$Q_{\tau}\left(LCO2_{it}\right) = \beta_{\tau} + \beta_{1\tau}LGDP_{it} + \beta_{2\tau}LGDP^{2}{}_{it} + \beta_{3\tau}LESACCE_{it} + \varepsilon_{it} \tag{13}$$

Model 4

$$Q_{\tau}\left(LCO2_{it}\right) = \beta_{0} + \beta_{1\tau}LGDP_{it} + \beta_{2\tau}LGDP^{2}{}_{it} + \beta_{3\tau}LESAFF_{it} + \varepsilon_{it} \tag{14}$$

where Q_{τ} is the regression parameters of the τth distributional point, while τ denotes the distributional point for the independent variables. Before we estimate the quantile regression model, normality and stationarity checking are performed among the selected variables. The first step involves testing the cross-section dependence of each variable using Pesaran's cross-sectional dependence (CD) test (Pesaran 2004). Then, the unit root test was performed using cross-sectionally augmented Dickey-Fuller (CADF) and cross-sectional dependence (CIPS) panel unit root tests. The basis of the CADF test is augmenting the augmented Dickey-Fuller (ADF) regression with the lagged cross-sectional mean and first difference to capture cross-sectional dependence, which originates from a single factor model and tests the existence of a unit root for cross-sections. The CIPS statistics were employed, which are based on the cross-sectional average of the individual CADF statistics. Thirdly, a co-integration test was performed using Westerlund (2007), followed by estimating long-term coefficients using the panel quantile regression method.

Table 5 Summary of the CD test

Variables	CD test	*p*-value
LCO2	17.342	0.000
LGDP	292.730	0.000
LGDP2	176.901	0.000
LESACC	20.057	0.000
LESACCE	57.840	0.000
LESAVA	96.829	0.000
LESAFF	171.120	0.000

Table 6 Summary of the panel unit root tests

Variables	CIPS test		CADF test	
	Level	*1st difference*	*Level*	*1st difference*
LCO2	– 0.465	– 5.716***	– 0.607	– 3.854***
LGDP	– 2.667	– 4.486***	– 1.925	– 6.388***
LGDP2	– 2.328	– 2.908***	– 1.608	– 5.867***
LESACC	– 2.892	– 2.467***	– 0.277	– 5.618***
LESACCE	– 0.759	– 3.016***	– 1.960	– 4.467***
LESAVA	– 0.287	– 1.558***	– 2.151	– 2.809***
LESAFF	– 3.026	– 1.9382**	– 1.868	– 5.527***

** and *** refer to statistical significance at the 5% and 1% levels, respectively

Empirical results and discussion

Preliminary check-ups

The cross-sectional dependence provided preliminary evidence of the heterogenous distribution by revealing a simple unconditional distribution across countries (You et al. 2015). Moreover, Pesaran's cross-sectional dependence (CD) test was employed (Pesaran 2004). Table 5 presents the findings of the CD analysis and illustrates that the null hypothesis of the cross-sectional dependence was rejected for all variables. Hence, this observation demonstrated that the dependent and independent variables in this country-based panel data analysis exhibited cross-sectional dependence.

The unit root computation was performed using the cross-sectionally augmented Dickey-Fuller (CADF).

Table 7 Summary of Westerland's cointegration test

Tests	Value	*p*-value	Cointegration
Model 1			
G_t	3.861	0.000***	Yes
G_a	11.989	0.000***	Yes
P_t	12.487	0.000***	Yes
P_a	7.470	0.000***	Yes
Model 2			
G_t	2.816	0.000***	Yes
G_a	19.296	0.000***	Yes
P_t	22.082	0.000***	Yes
P_a	13.119	0.000***	Yes
Model 3			
G_t	3.951	0.000***	Yes
G_a	16.928	0.000***	Yes
P_t	19.797	0.000***	Yes
P_a	10.683	0.000***	Yes
Model 4			
G_t	4.386	0.000***	Yes
G_a	17.412	0.000***	Yes
P_t	25.756	0.000***	Yes
P_a	14.739	0.000***	Yes

*** refers to statistical significance at the 1% level

Furthermore, the cross-sectionally augmented IPS approaches were based on cross-sectional dependence (CIPS). Table 6 reports the results of the CIPS and CADF tests, illustrating that the null hypothesis could not be ruled out for all the variables. The series was determined to produce a unit root at the level while becoming stationary at the first difference. Thus, the long-term coefficients were estimated using panel quantile regression.

Cointegration test

As can be seen from Table 7, Westerlund (2007) cointegration test was employed to explore the long-run correlation among the variables. Westerlaud's cointegration includes four normally distributed tests, namely, G_a (among groups), G_t (between groups), P_a (among panels), and P_t (between panels) (Westerlund 2007; Salman et al. 2019). G_t and G_a denote *t*-test statistics and the estimated coefficient for group mean tests, while P_t and P_a for whole panel tests. The results reveal that all four test statistics rejected the null hypothesis of no co-integration, proving that the variables are correlated in the long run.

Panel quantile regression results

The empirical results of a quantile regression analysis that examined the link between carbon emissions and energy security in 112 developing nations are presented in Table 8. The four model specifications were created to determine the disaggregated impact of the 4As of energy security on carbon emissions. Moreover, the models were primarily estimated using the pooled OLS regression method to comprehend panel quantile regression better and facilitate comparison. In Table 8, column 1 illustrates the pooled OLS regression estimates. The following columns represent the 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th percentiles of conditional carbon emissions distribution. Percentiles below 50th were classified as lower quartiles, while those above 50th represented upper quartiles.

The findings of the OLS regression suggested that the estimated GDP and GDP^2 coefficients are significant with a positive and a negative sign, respectively. According to the long-term coefficients, a 1% rise in GDP led to an increase in carbon emissions of 1.8% to 2.8%. Alternatively, a rise in GDP^2 is predicted to result in a decrease from 0.095 to 0.140%. The findings mentioned above support the presence of the EKC hypothesis indicated by Isik et al. (2021) for OECD countries, Altarhouni et al. (2021) and Qashou et al. (2022) for Turkey, Fatima et al. (2021) for high-emitter countries, Zeraibi et al. (2022) for China, and Shittu et al. (2021) for Asian countries. The EKC prediction, which suggested an inverted U-shaped relationship between carbon emissions and economic growth, was also verified for models 1 to 4, thus indicating that while economic growth initially causes increased CO2 emissions, it eventually causes CO2 emissions to decline. Hence, the findings for the panel of countries demonstrated that the EKC hypothesis holds in these nations.

Concerning the 4As of energy security, the variable energy security observed a mixed effect on carbon emission. Energy availability is the key factor in reducing environmental emissions due to their significant negative impact on carbon emissions. According to the significant negative coefficient of energy availability, a nation with a larger energy supply capacity might have lower levels of carbon emissions. This result is consistent with that of Shittu et al. (2021), who measured energy security as energy availability and discovered that it reduced environmental emissions in Asian countries. The finding that more energy supply capacity may result in lower levels of carbon emissions can be directly linked to the acquisition of abundant energy resources by developing countries, such as biomass, geothermal energy, solar energy, and wind power. For instance, India has emerged as one of the world's leaders in solar energy deployment owing to its geographic location, which provides adequate sunlight all year round. Likewise, Brazil has a substantial amount of biomass resources, mainly sugarcane bagasse and other agricultural waste. Bagasse is a biomass fuel in the country's sugar and ethanol industries to generate energy and heat, which decreases dependency

Table 8 Summary of the quantile regression results

Variables	OLS	Quantile levels								
		10th	20th	30th	40th	50th	60th	70th	80th	90th
Model 1										
LGDP	2.862*** (0.005)	3.507*** (0.000)	4.033*** (0.000)	3.764*** (0.000)	3.612** (0.025)	3.394 (0.119)	0.1322*** (0.000)	2.759 (0.249)	2.856*** (0.000)	1.682 (0.179)
LGDP^2	− 0.140*** (0.00)	− 0.148*** (0.000)	− 0.179*** (0.000)	− 0.165*** (0.000)	− 0.159** (0.018)	− 0.149 (0.251)	− 3.286 (0.252)	− 0.1150 (0.301)	− 0.124 (0.210)	− 0.061 (0.445)
LESAVA	− 0.269*** (0.000)	− 0.215*** (0.008)	− 0.255** (0.045)	− 0.268* (0.081)	− 0.269** (0.016)	− 0.276** (0.039)	0.2989 (0.572)	− 0.320 (0.174)	− 0.405 (0.239)	− 0.374 (0.142)
Intercept	− 13.158*** (0.000)	− 18.784*** (0.000)	− 7.482*** (0.000)	− 19.285*** (0.000)	− 18.224*** (0.000)	-16.977*** (0.000)	15.528*** (0.000)	13.748*** (0.000)	13.634*** (0.000)	7.899*** (0.000)
Model 2										
LGDP	2.626*** (0.003)	2.027 (0.114)	2.077 (0.229)	1.980** (0.042)	0.967 (0.501)	1.843 (0.620)	1.780 (0.112)	1.502*** (0.000)	0.722* (0.074)	2.138* (0.069)
LGDP^2	− 0.128*** (0.000)	− 0.073 (0.387)	− 0.075 (0.162)	− 0.071 (0.070)	− 0.071 (0.247)	− 0.065 (0.233)	− 0.062 (0.752)	− 0.050** (0.039)	− 0.062* (0.052)	− 0.088** (0.021)
LESACC	0.274*** (0.000)	0.671** (0.042)	0.660*** (0.000)	0.642*** (0.007)	0.635 (0.885)	0.663 (0.119)	0.704 (0.686)	0.840 (0.787)	0.877 (0.398)	− 0.821 (0.399)
Intercept	− 13.122*** (0.000)	− 14.663*** (0.000)	− 14.626*** (0.000)	− 13.881*** (0.000)	− 13.590*** (0.000)	− 9.652*** (0.000)	− 12.701*** (0.000)	− 11.657*** (0.000)	− 12.474*** (0.000)	− 13.577*** (0.000)
Model 3										
LGDP	2.177*** (0.000)	3.227** (0.015)	3.276** (0.028)	3.121 (0.313)	2.931 (0.721)	2.501 (0.369)	2.2320* (0.065)	1.939* (0.069)	1.706** (0.044)	1.946** (0.028)
LGDP^2	− 0.098*** (0.007)	− 0.137** (0.036)	− 0.142** (0.032)	0.135 (0.278)	− 0.126 (0.269)	− 0.103 (0.734)	− 0.088 (0.043)	− 0.0744 (0.026)	− 0.064 (0.084)	− 0.079 (0.066)
LESACCE	0.652** (0.031)	0.040*** (0.001)	0.033*** (0.000)	0.046** (0.030)	0.062*** (0.000)	0.073 (0.401)	0.101 (0.801)	0.082 (0.160)	0.086 (0.208)	0.095 (0.748)
Intercept	− 9.656*** (0.002)	16.555*** (0.000)	− 16.317*** (0.000)	15.296*** (0.000)	− 14.180*** (0.000)	12.085*** (0.000)	10.674*** (0.009)	− 9.043** (0.047)	7.368*** (0.000)	− 8.135*** (0.000)
Model 4										
LGDP	1.826*** (0.000)	2.947** (0.032)	3.410* (0.086)	3.688 (0.573)	3.623 (0.299)	1.600 (0.712)	3.435* (0.075)	3.058* (0.082)	0.826** (0.036)	1.528*** (0.006)
LGDP^2	− 0.095*** (0.006)	− 0.124* (0.065)	− 0.149** (0.018)	− 1.164 (0.716)	− 0.163 (0.368)	− 0.541 (0.087)	− 0.153** (0.028)	− 0.133* (0.064)	− 0.124** (0.032)	− 0.052** (0.036)
LESAFF	0.388*** (0.000)	0.192** (0.027)	0.157 (0.969)	0.124 (0.347)	0.140* (0.072)	0.135* (0.062)	0.145 (0.332)	0.1540 (0.735)	0.1614 (0.405)	0.156 (0.992)
Intercept	− 7.333*** (0.000)	15.704*** (0.0	7.560** (0.036)	8.650** (0.013)	− 7.978*** (0.000)	− 10.429*** (0.000)	− 16.863*** (0.000)	− 14.963*** (0.000)	− 13.476*** (0.000)	− 7.311*** (0.000)

*, **, *** refer to statistical significance at the 5%, 1%, and 10% levels, respectively

on fossil fuels and contributes to lower carbon emissions. However, energy acceptance, accessibility, and affordability acquired a positive impact on carbon emissions, indicating that these factors are a cause of increasing emissions. The obstacle to energy security, such as lack of adequate technological capacity, high energy supply costs, poor distribution infrastructure, insufficient regulation, and a lack of comprehensive understanding of energy, can impede emissions reduction initiatives.

The results of the quantile regression analysis indicated several significant differences between the percentiles and that the influence of independent factors on carbon emissions was heterogeneous. At the 10th, 20th, 30th and 40th quantiles of model 1, the GDP and GDP^2 coefficients were significantly positive and negative, respectively, implying the existence of an inverted U-shaped relationship between income and emission, similar to You et al. (2015), Salman et al. (2019), and Eren (2022). On the contrary, the results did not support the EKC hypothesis for the remaining quantiles, which stated that GDP raised CO2 emissions and that the GDP^2 impact on carbon emission was insignificant at upper quantiles. The results of this study align with Zhu et al. (2016), Gorus and Aslan (2019), as well as Halliru et al. (2020), providing support for the invalid EKC hypothesis at low quantiles. Although the OLS results supported the EKC hypothesis, the results of models 2 to 4 demonstrated that the EKC hypothesis was unsupported at all quantile levels. The GDP coefficient and GDP^2 coefficient were negligibly positive and negative at specific lower and upper quantiles, respectively. Here, it can be seen that there were significant differences between quantiles in the relationship between income and carbon emission. These findings are consistent with those of You et al. (2015), Zhang et al. (2016), and Allard et al. (2018), who found that the use of quantile regressions resulted in the inconclusive shape of the EKC.

The findings from the quantile regressions regarding the 4As of energy security were ambiguous across different quantiles. The estimated coefficient for energy availability was negative at the lower and upper quantiles but insignificant at the upper quantiles. While there was an indication for carbon emissions to decline as energy availability rose, the insignificant coefficient at the upper quantiles suggests that energy availability alone might not be the main factor in reducing carbon emissions. Instead, the lack of significance suggested that at higher stages of economic development, other factors, such as changes in industrial structure, laws, regulations, or technology breakthroughs, may have a higher influence in determining carbon emissions. The other energy security dimensions involved in models 2 to 4 were also insightful. The influence of energy accessibility on carbon emission was heterogeneous across quantiles, as it was significant and positive at the 10th and 20th quantiles. Conversely, the coefficient became insignificant at the 30th quantile and above. This observation inferred the small size of energy security in developing countries and insufficient to mitigate carbon emissions. For instance, a significant portion of the population in sub-Saharan Africa lacks access to reliable electricity. The shift to low-carbon alternative options is hampered by inadequate access to modern, clean energy services, making it challenging to effectively reduce carbon emissions. As a result, people depend on alternate energy sources like kerosene lights and diesel generators, which have substantial carbon emissions and adverse environmental effects.

The energy affordability and acceptability coefficients were positive and significant at lower quartiles, supporting the pooled OLS regression result. Higher carbon emissions may arise as energy prices rise. When energy options are more expensive, people might be less likely to spend money on renewable energy sources or energy-efficient technologies, which could result in an ongoing reliance on less expensive but more environmentally damaging energy sources, raising carbon emissions. For example, in Nigeria, the price of electricity produced from conventional fossil fuel sources, including gasoline and diesel, is relatively lower than renewable energy alternatives. People find it challenging to invest in renewable energy as they often encounter greater upfront costs due to this pricing gap.

Regarding energy acceptance, the findings showed that developing countries' populations do not consider renewable energy sources or energy-efficient technology acceptable or appropriate for their needs and may choose more carbon-intensive energy options. There may be an increase in carbon emissions because of the choice of less environmentally favourable options. For instance, rural communities in Bangladesh find renewable energy sources unfamiliar or less acceptable due to cultural norms, a lack of knowledge or a preference for conventional techniques, despite government efforts to promote renewable energy options, including solar household systems. This preference for energy sources with a high carbon footprint hinders the switch to cleaner energy systems and increases carbon emissions.

Table 9 summarises the panel quantum estimation of the coefficient of indication. Overall, this study discovered that lower quantiles of model 1 of the GDP and GDP^2 series produced a negative and positive sign, respectively. Only the GDP and GDP^2 series supported the EKC hypothesis at the high quantiles for models 2 and 4. The energy availability series displayed a negative sign at the low and middle quantiles, but the sign was insignificant at the high quantiles. Finally, the results revealed that all predicted lower quantiles of the accessibility, affordability, and acceptability of energy series acquired a statistically significant positive sign.

Figures 1, 2, 3, and 4 demonstrate the quantile effects of each variable for each model. The effect of GDP on CO2

Table 9 Summary of the quantile regression

Variables	10th	20th	30th	40th	50th	60th	70th	80th	90th
Model 1									
LGDP	+	+	+	+	/	+	/	+	/
LGDP^2	–	–	–	–	/	/	/	/	/
LESAVA	–	–	–	–	–	/	/	/	/
Model 2									
LGDP	/	/	+	/	/	/	+	+	+
LGDP^2	/	/	/	/	/	/	–	–	–
LESACC	+	+	+	/	/	/	/	/	/
Model 3									
LGDP	+	+	/	/	/	+	+	+	+
LGDP^2	–	–	/	/	/	/	/	/	/
LESACCE	+	+	+	+	/	/	/	/	/
Model 4									
LGDP	+	+	/	/	/	+	+	+	+
LGDP^2	–	–	/	/	/	–	–	–	–
LESAFF	+	/	/	+	+	/	/	/	/

"+" and "–" denote a statistically significant positive and negative relationships, respectively. "/" denotes an insignificant relationship

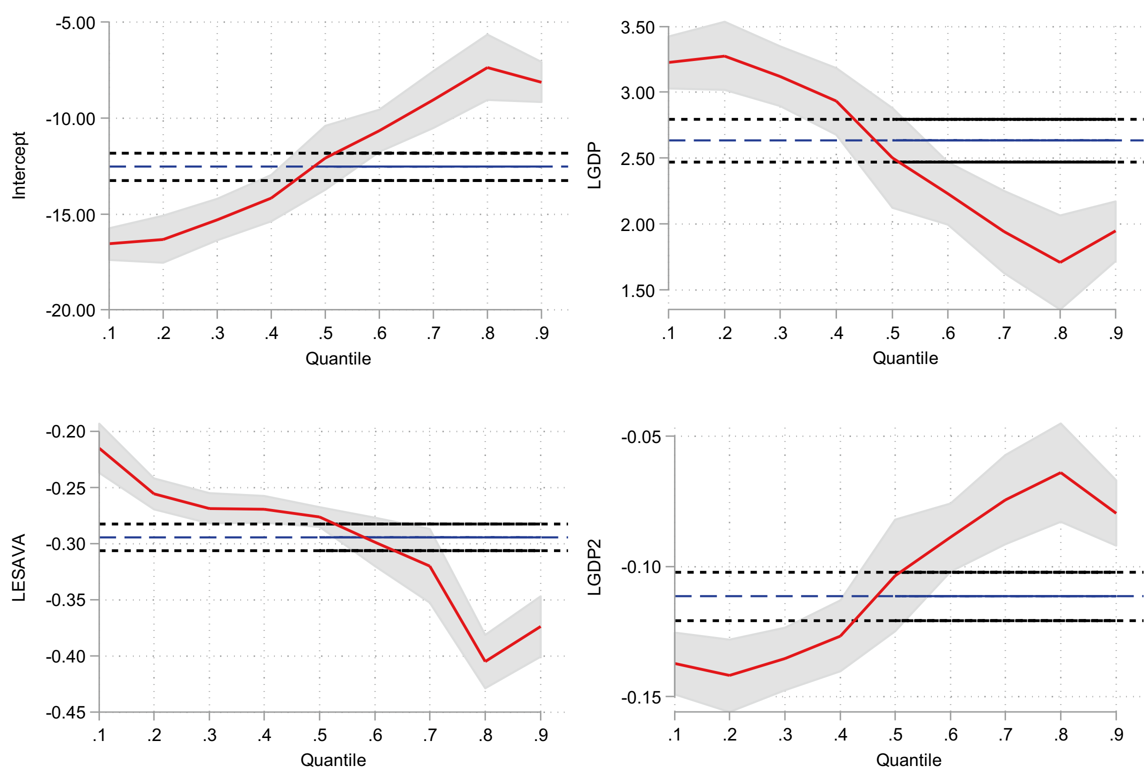

Fig. 1 Variation in panel quantile regressions coefficients for model 1. Note: The red curve reveals the impact of each factor on CO2 emissions at different quantiles. The straight blue line indicates the results of the regression. The black dotted line represents the 95% confidence curve of the OLS estimation. The shaded area represents a 95% confidence interval for the quantile regression

emissions decreased with increasing quantile. Another finding was that the GDP^2 coefficients consistently decreased as they moved from lower to higher quantiles. The graphs also portrayed an inverted U-shaped relationship between income and carbon emissions, with emissions rapidly increasing up to the middle and declining

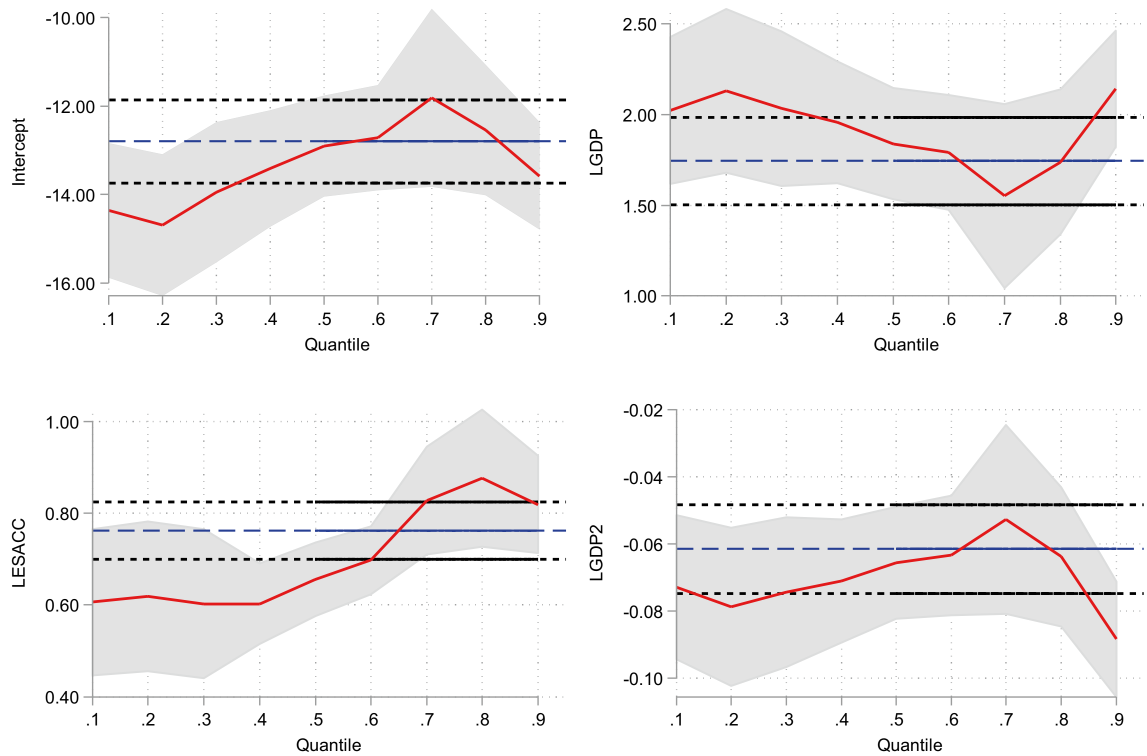

Fig. 2 Variation in panel quantile regressions coefficients for model 2. Note: The red curve reveals the impact of each factor on CO2 emissions at different quantiles. The straight blue line indicates the results of the regression. The black dotted line represents the 95% confidence curve of the OLS estimation. The shaded area represents a 95% confidence interval for the quantile regression

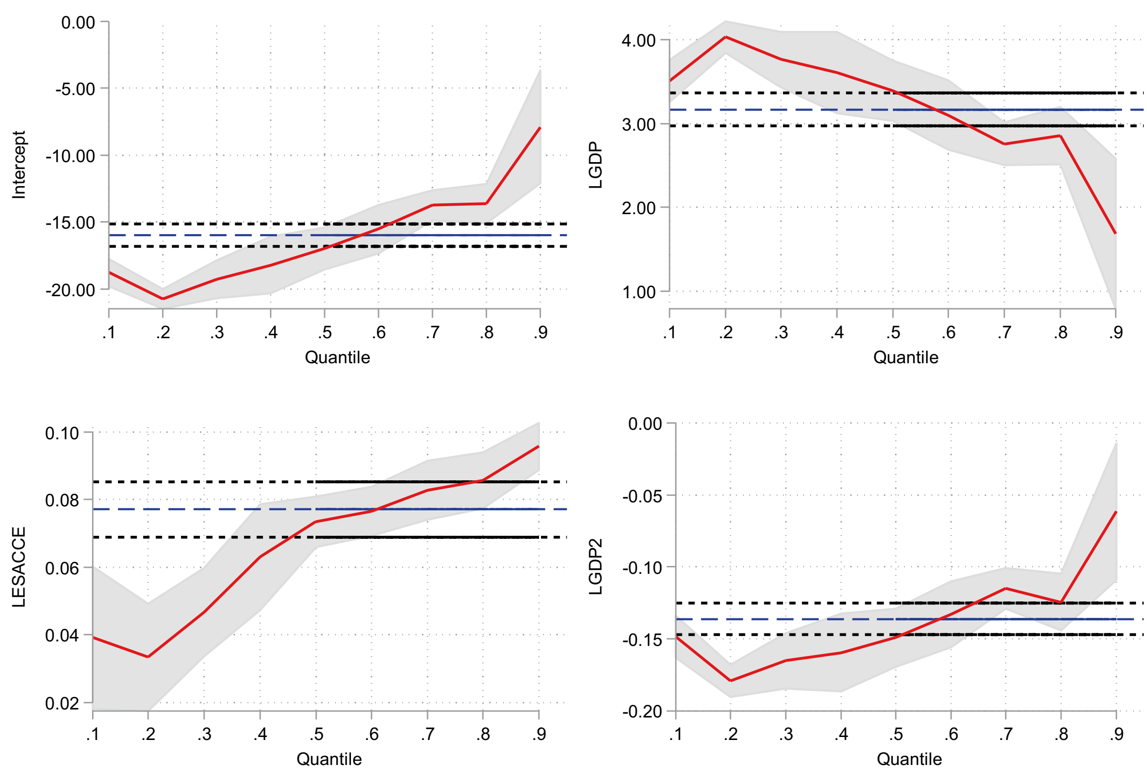

Fig. 3 Variation in panel quantile regressions coefficients for model 3. Note: The red curve reveals the impact of each factor on CO2 emissions at different quantiles. The straight blue line indicates the results of the regression. The black dotted line represents the 95% confidence curve of the OLS estimation. The shaded area represents a 95% confidence interval for the quantile regression

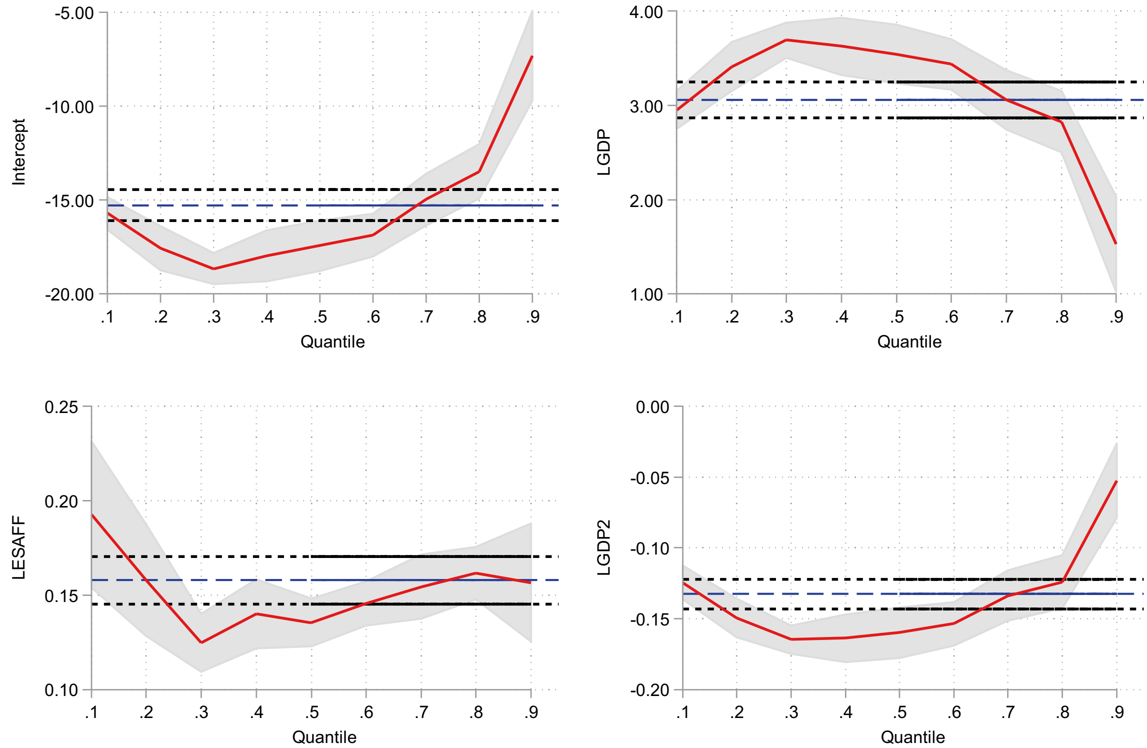

Fig. 4 Variation in panel quantile regressions coefficients for model 4. Note: The red curve reveals the impact of each factor on CO2 emissions at different quantiles. The straight blue line indicates the results of the regression. The black dotted line represents the 95% confidence curve of the OLS estimation. The shaded area represents a 95% confidence interval for the quantile regression

to the right tail in the upper quantile. The sloped coefficients of energy availability were also decreasing across the quantile. In contrast, the coefficient of energy accessibility, affordability, and acceptability tended to rise from lower to higher quantile levels. The overall findings suggested that energy security considerations in the transition to low emissions have not yet been effectively realised and require additional efforts in developing countries, which contrasted with You et al. (2015) and Salman et al. (2019). Additionally, these findings contradict the findings of You et al. (2015) and Salman et al. (2019), which support the idea that investing in energy security measures, such as energy efficiency, renewables, and electric transportation, can reduce reliance on imported oil and gas while also promoting environmental protection to reduce emission countries.

The robustness check is also performed by applying an alternative environmental degradation indicator, including nitrous oxide (N2O), methane (CH4), and fluorinated gases (F-GAS). Tables 10, 11, and 12 are almost identical to the results obtained in Table 8. This study also offers a summary of the panel quantile models with nitrous oxide (N2O), methane (CH4), and fluorinated gases (F-GAS) as measures of environmental deterioration to conserve space and make it easier for readers (see Table 13).

Conclusion

The panel quantile regression has been employed in this study to examine the 4As impact of energy security on CO2 emissions. This study utilised a global sample of 112 developing countries from 1990 to 2019. Particularly, the validity of the EKC hypothesis was investigated for the first time using the 4As of energy security in developing countries. Based on the empirical results, the impact of explanatory variables on carbon emissions was heterogeneous, with pronounced differences across various quantiles. The following conclusions were drawn from this study. Firstly, the results confirmed the EKC correlation between income and carbon emission only at high quantiles for energy availability and affordability, except for energy availability and acceptability. Secondly, the effect of energy security on carbon emission was heterogeneous across the models. The energy availability significantly negatively affected carbon emission in low and high quantiles. The effect of energy accessibility and acceptability on carbon emissions was positive, implying that it did not mitigate CO2 emissions. Thus, it hinted that developing countries could not adapt and access sustainable modern energy services and products, leading to dependence on foreign fossil fuels and increased emissions.

Table 10 The quantile regression results for alternative environmental degradation indicator (N2O)

Variables	OLS	Quantile levels								
		10th	20th	30th	40th	50th	60th	70th	80th	90th
Model 1										
LGDP	0.499***	0.128***	0.127***	0.116***	0.515***	0.114***	0.147***	0.180	0.268***	0.910
	[0.003]	[0.002]	[0.003]	[0.006]	[0.000]	[0.000]	[0.000]	[0.456]	[0.008]	[0.550]
LGDP²	− 0.140***	− 0.340**	− 0.687***	− 0.248***	− 0.338***	0.511	0.484	0.648	0.250	0.110
	[0.001]	[0.007]	[0.000]	[0.000]	[0.000]	[0.209]	[0.184]	[0.289]	[0.183]	[0.294]
LESAVA	− 0.213***	− 0.113***	− 0.709*	− 0.120***	− 0.253***	− 0.200**	0.108	− 0.158	0.153	0.133
	[0.000]	[0.000]	[0.070]	[0.009]	[0.001]	[0.000]	[0.329]	[0.256]	[0.193]	[0.210]
Intercept	− 0.537*	− 0.137**	− 0.486***	− 0.236***	− 0.150***	0.772***	− 0.776***	− 0.267***	0.258***	− 0.306
	[0.000]	[0.000]	[0.001]	[0.000]	[0.000]	[0.005]	[0.000]	[0.000]	[0.000]	[0.002]
Model 2										
LGDP	0.490***	0.395	0.684	0.676***	0.997	0.162	0.231	0.708**	0.592**	0.680*
	[0.000]	[0.357]	[0.574]	[0.000]	[0.250]	[0.403]	[0.850]	[0.000]	[0.030]	[0.000]
LGDP²	− 0.101***	0.240	0.104	0.256	0.401	0.140	0.120	− 0.272	− 0.509	− 0.410
	[0.004]	[0.758]	[0.481]	[0.249]	[0.520]	[0.255]	[0.202]	[0.000]	[0.000]	[0.000]
LESACC	0.133**	0.209***	0.230***	0.510***	0.305	0.159	0.110	0.120	0.711	0.711
	[0.000]	[0.000]	[0.00]	[0.007]	[0.241]	[0.443]	[0.178]	[0.672]	[0.361]	[0.148]
Intercept	− 0.260*	− 0.218***	− 0.221***	− 0.208***	− 0.290	− 0.479*	− 0.170***	− 0.228***	− 0.410***	− 0.112***
	[0.000]	[0.000]	[0.000]	[0.007]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Model 3										
LGDP	0.311	0.855	0.131	0.124***	− 0.298	0.386***	0.174	0.472***	0.319***	0..749***
	[0.000]	[0.267]	[0.280]	[0.001]	[0.278]	[0.279]	[0.251]	[0.003]	[0.000]	[0.000]
LGDP²	− 0.811	0.602	0.077	0.107	0.210	0.310	0.306***	− 0.344***	− 0.507***	− 0.470***
	[0.000]	[0.216]	[2.04]	[0.392]	[0.180]	[0.191]	[0.883]	[0.007]	[0.000]	[0.000]
LESACCE	0.102*	0.222**	0.310***	0.507*	0.111	0.259**	0.220***	0.178***	0.848***	0.267***
	[0.000]	[0.172]	[0.000]	[0.000]	[0.211]	[0.217]	[0.363]	[0.399]	[0.761]	[0.270]
Intercept	− 0.522	− 0.190*	− 0.247***	− 0.606***	0.183	− 0.557***	− 0.203***	− 0.229***	− 0.877***	− 0.393*
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Model 4										
LGDP	0.904***	0.991***	0.822***	0.893***	0.960***	0.928***	0.719***	0.927***	0.749***	0.199***
	[0.000]	[0.691]	[0.783]	[0.588]	[0.621]	[0.805]	[0.663]	[0.538]	[0.000]	[0.000]
LGDP²	− 0.229***	0.638***	0.622***	0.403**	0.303*	0.246**	0.314***	− 0.140***	− 0.313***	− 0.332
	[0.000]	[0.288]	[0.269]	[0.219]	[0.189]	[0.516]	[0.551]	[0.000]	[0.000]	[0.000]
LESAFF	0.108*	0.509*	0.224*	0.257***	0.372***	0.238***	0.134***	0.230***	0.240***	0.607***
	[0.002]	[0.000]	[0.000]	[0.000]	[0.509]	[0.001]	[0.492]	[0.266]	[0.410]	[0.246]
Intercept	− 0.500***	− 0.390***	− 0.411***	− 0.537*	− 0.509**	− 0.554***	− 0.503***	− 0.112*	0.012*	− 1.545***
	[0.000]	[0.000]	[0.000]	[0.008]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]

*, **, and *** refer to statistical significance at the 5%, 1%, and 10% levels, respectively

Table 11 The quantile regression results for alternative environmental degradation indicator (CH4)

Variables	OLS	Quantile levels								
		10th	20th	30th	40th	50th	60th	70th	80th	90th
Model 1										
LGDP	0.516*** [0.00]	0.470*** [0.000]	0.640*** [0.000]	0.217*** [0.000]	0.211** [0.000]	0.910* [0.000]	0.821*** [0.000]	− 0.611*** [0.414]	0.785* [0.000]	− -0.840** [0.217]
LGDP^2	− 0.203* [0.002]	− 0.332*** [0.007]	− 0.912* [0.000]	− 0.296*** [0.000]	− 0.205*** [0.670]	− 0.710*** [0.346]	0.251*** [0.282]	0.160*** [0.504]	− 0.230* [0.208]	− 0.210* [0.204]
LESAVA	− 0.140** [0.000]	− 0.109*** [0.000]	− 0.540** [0.020]	− 0.530** [0.000]	0.501* [0.281]	− 0.215*** [0.490]	0.220** [0.221]	0.250* [0.194]	0.651** [0.221]	0.962*** [0.278]
Intercept	− 0.211*** [0.000]	− 0.170** [0.000]	− 0.150* [0.000]	− 0.310*** [0.000]	− 0.180** [0.000]	− 0.807** [0.000]	− 0.449*** [0.000]	− 0.310 [0.006]	− 0.276 [0.000]	− 0.559 [0.000]
Model 2										
LGDP	0.660* [0.002]	0.287** [0.231]	0.576*** [0.306]	0.807*** [0.000]	0.694*** [0.984]	0.570*** [0.257]	0.826*** [0.831]	0.592*** [0.000]	0.796*** [0.000]	0.937*** [0.000]
LGDP^2	− 0.240** [0.000]	0.303*** [0.260]	0.305*** [0.245]	0.262*** [0.831]	0.630* [0.185]	0.551*** [0.260]	0.393*** [0.340]	− 0.320** [0.000]	− 0.210* [0.001]	− 0.530* [0.000]
LESACC	0.408** [0.000]	0.241* [0.000]	0.218** [0.000]	0.304* [0.000]	0.208*** [0.497]	0.230*** [0.610]	0.760*** [0.290]	0.410** [0.227]	0.581*** [0.324]	0.206*** [0.617]
Intercept	− 0.210*** [0.000]	− 0.560*** [0.000]	− 0.720*** [0.000]	− 0.903*** [0.000]	− 0.538*** [− 0.001]	0.490*** [0.000]	− 0.300** [0.004]	− 0.711*** [0.000]	− 0.820*** [0.000]	− 0.805*** [0.000]
Model 3										
LGDP	0.269*** [0.000]	0.899*** [0.000]	0.298*** [0.000]	0.210* [0.514]	− 0.160* [0.581]	− 0.170*** [0.699]	0.220* [0.000]	0.320*** [0.000]	0.491*** [0.000]	0.329*** [0.000]
LGDP^2	− 0.395* [0.752]	0.369* [0.195]	0.252* [0.180]	− 0.140*** [0.435]	− 0.216*** [0.752]	− 0.186*** [0.661]	− 0.114*** [0.000]	− 0.190*** [0.000]	− 0.172*** [0.000]	− 0.187*** [0.000]
LESACCE	0.106** [0.020]	0.566*** [0.000]	0.303*** [0.008]	0.317* [0.821]	0.162* [0.891]	0.278*** [0.535]	0.214* [0.481]	− 0.477*** [0.905]	0.561*** [0.960]	− 0.300*** [0.266]
Intercept	− 0.974* [0.000]	− 0.886* [0.000]	− 0.842* [0.000]	− 0.697*** [0.000]	− 0.673*** [0.000]	− 0.825** [0.000]	− 0.916*** [0.000]	0.842*** [0.000]	0.952*** [0.000]	0.720*** [0.000]
Model 4										
LGDP	0.219*** [0.000]	0.170*** [0.329]	0.264*** [0.865]	0.177*** [0.000]	0.211** [0.229]	− 0.190* [0.490]	0.128*** [0.369]	0.161*** [0.000]	0.264* [0.000]	− 0.278** [0.000]
LGDP^2	− 0.382* [0.000]	0.270*** [0.241]	0.192* [0.691]	0.195*** [0.696]	0.151*** [0.488]	− 0.170*** [0.355]	− 0.251*** [0.000]	− 0.360*** [0.0005]	− 0.352** [0.000]	− 0.330*** [0.000]
LESAFF	0.104** [0.000]	0.120*** [0.000]	0.451** [0.000]	0.153** [0.000]	0.100* [0.699]	0.109*** [0.682]	0.220** [0.560]	0.125* [0.491]	0.482** [0.812]	0.104* [0.698]
Intercept	0.622*** [0.000]	− 0.710** [0.000]	0.105* [0.000]	− 0.301*** [0.000]	− 0.801** [0.000]	0.617** [0.000]	− 0.490*** [0.000]	0.811* [0.000]	− 0.621*** [0.000]	0.322*** [0.000]

*, **, and *** refer to statistical significance at the 5%, 1%, and 10%, levels, respectively

Table 12 The quantile regression results for alternative environmental degradation indicator (F-GAS)

Variables	OLS	Quantile levels								
		10th	20th	30th	40th	50th	60th	70th	80th	90th
Model 1										
LGDP	0.576***	0.280***	0.294***	0.350***	0.268***	0.259***	0.296***	0.379***	0.257***	0.278***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.520]	[0.000]	[0.975]	[0.000]	[0.542]
LGDP^2	− 0.350***	− 0.126***	− 0.163*	− 0.150***	− 0.093***	0.332**	0.120*	0.235*	− 0.132	0.149
	[0.000]	[0.000]	[0.000]	[0.000]	[0.005]	[0.626]	[0.521]	[0.771]	[0.621]	[0.407]
LESAVA	− 0.128**	− 0.340*	0.028***	− 0.230***	− 0.176***	− 0.140**	0.059***	0.156***	0.221***	0.290***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.324]	[0.617]	[0.521]	[0.356]
Intercept	0.227***	− 0.229***	− 0.830***	− 0.491***	− 0.833**	0.711***	− 0.428***	0.358***	− 0.423**	− 0.419***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Model 2										
LGDP	0.113*	0.247**	0.172***	0.419***	− 0.267*	− 0.285**	− 0.167***	0.234***	0.377*	0.320*
	[0.000]	[0.531]	[0.567]	[0.000]	[0.482]	[0.812]	[0.493]	[0.000]	[0.000]	[0.000]
LGDP^2	− 0.981	0.162***	0.272*	− 0.211*	0.098***	0.186**	0.096***	− 0.197***	− 0.230***	− 0.139***
	[0.000]	[0.656]	[0.691]	[0.591]	[0.290]	[0.322]	[0.203]	[0.000]	[0.000]	[0.000]
LESACC	0.182***	0.246**	0.180*	0.275**	0.140***	0.211***	0.138***	0.612*	− 0.194***	− 0.092*
	[0.000]	[0.000]	[0.000]	[0.000]	[0.772]	[0.375]	[0.504]	[0.394]	[0.446]	[0.182]
Intercept	0.532*	− 0.278*	0.772***	0.502***	− 0.556*	− 0.430*	− 0.245*	− 0.622*	− 0.470***	− 0.514*
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Model 3										
LGDP	0.249	-− .204*	− 0.250***	0.248***	0.147**	0.2991**	0.241**	0.220**	0.296**	0.253***
	[0.000]	[0.000]	[0.000]	[0.475]	[0.295]	[0.772]	[0.000]	[0.000]	[0.000]	[0.000]
LGDP^2	0.538***	− 0.106*	0.370***	0.154*	0.075*	− 0.171*	0.196*	− 0.532***	− 0.098**	− 0.547***
	[0.000]	[0.000]	[0.000]	[0.299]	[0.198]	[0.223]	[0.286]	[0.841]	[0.225]	[0.841]
LESACCE	0.167***	0.146***	0.208***	0.263***	0.263**	− 0.183**	− 0.095***	− 0.199**	− 0.121	0.321*
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.321]	[0.298]	[0.337]	[0.351]	[0.991]
Intercept	0.712***	0.701***	0.555	0.904**	0.663**	0.729***	0.601**	0.851***	0.541***	0.621**
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.001]	[0.000]
Model 4										
LGDP	0.231***	0.332***	− 0.205**	0.295***	− 0.288**	− 0.210***	0.221***	0.188***	0.205**	0.195***
	[0.000]	[0.000]	[0.000]	[0.752]	[0.838]	[0.349]	[0.000]	[0.000]	[0.000]	[0.000]
LGDP^2	− 0.508***	− 0.216***	− 0.320*	0.449*	0.108*	0.185***	− 0.190***	− 0.096	− 0.357*	− 0.385*
	[0.000]	[0.000]	[0.000]	[0.859]	[0.292]	[0.254]	[0.000]	[0.000]	[0.000]	[0.000]
LESAFF	0.175	0.130***	0.092***	0.113***	0.269***	0.556***	0.084***	0.244***	0.212***	0.113***
	[0.000]	[0.000]	[0.271]	[0.364]	[0.000]	[0.000]	[0.177]	[0.500]	[0.627]	[0.352]
Intercept	0.351***	− 0.560***	− 0.610***	− 0.417***	− 0.560***	− 0.445***	0.839***	− 0.366***	− 0.610***	− 0.417***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]

*, **, and *** refer to statistical significance at the 5%, 1%, and 10% levels, respectively

Table 13 Summary of the quantile regression for alternative environmental degradation indicator (N2O, CH4, F-GAS)

Variables	N2O									CH4									F-GAS								
	10th	20th	30th	40th	50th	60th	70th	80th	90th	10th	20th	30th	40th	50th	60th	70th	80th	90th	10^{th}	20^{th}	30^{th}	40^{th}	50^{th}	60^{th}	70^{th}	80^{th}	90^{th}
Model 1																											
LGDP	+	+	+	+	+	+	/	+	/	+	+	+	+	+	+	/	+	/	+	+	+	+	/	+	/	+	/
LGDP^2	–	–	–	–	/	/	/	/	/	–	–	–	/	/	/	/	/	/	–	–	–	–	/	/	/	/	/
LESAVA	–	–	–	–	–	/	/	/	/	–	–	–	/	/	/	/	/	/	–	–	–	–	–	/	/	/	/
Model 2																											
LGDP	/	/	+	/	/	/	+	+	+	/	/	+	/	/	/	+	+	+	/	/	+	/	/	/	+	+	+
LGDP^2	/	/	/	/	/	/	–	–	–	/	/	/	/	/	/	–	–	–	/	/	/	/	/	/	–	–	–
LESACC	+	+	+	/	/	/	/	/	/	+	+	+	/	/	/	/	/	/	+	+	+	/	/	/	/	/	/
Model 3																											
LGDP	/	/	+	/	/	/	+	+	+	+	+	+	/	/	/	+	+	+	+	+	/	/	/	+	+	+	+
LGDP^2	/	/	/	/	/	/	–	–	–	/	/	/	/	/	/	–	–	–	–	–	/	/	/	/	/	/	/
LESACCE	+	+	+	/	/	/	/	/	/	+	+	+	/	/	/	/	/	/	+	+	+	+	/	/	/	/	/
Model 4																											
LGDP	/	/	/	/	/	/	+	+	+	/	/	+	/	/	/	+	+	+	+	+	/	/	/	+	+	+	+
LGDP^2	/	/	/	/	/	/	–	–	–	/	/	/	/	/	–	–	–	–	–	–	/	/	/	–	–	–	-
LESAFF	+	+	+	/	/	/	/	/	/	+	+	+	/	/	/	/	/	/	+	/	/	+	+	/	/	/	/

"+" and "–" denote a statistically significant positive and negative relationships, respectively. "/" denotes an insignificant relationship

This study offers policy implications for developing countries that aim to address energy security to decrease carbon emissions, taking into consideration of empirical findings. Although most developing countries have abundant energy resources, several barriers were encountered, such as high initial costs, limited awareness, and a lack of appropriate technologies. To address these barriers, governments must establish feed-in tariffs, quotas, loans, and project financing to improve access to affordable energy. For instance, in low-income countries, the main obstacle often lies in the expensive upfront expenses of renewable energy solutions. To solve this, governments can offer low-interest loans, and project financing alternatives can promote the development and deployment of renewable energy projects, making them more accessible and affordable for communities. Lack of specialised infrastructure and technologies may hinder developing nations with upper-middle incomes. Governments may deal with this problem by promoting collaborations with technology providers and encouraging the exchange of information and skills about renewable energy systems. By providing financial incentives like tax breaks or subsidies, governments may promote clean energy technology and energy security. Additionally, for lower-middle-income countries to effectively cut carbon emissions, governments must address both the availability and affordability of energy. One approach is to increase energy availability by enhancing access to affordable energy sources and growing energy distribution networks. Measures such as adopting subsidy programs to make energy services affordable for everyone can encourage the use of renewable energy sources. In addition to energy security, the government must encourage sustainable urban planning by fostering compact urban growth, efficient public transit systems, and green infrastructure. This approach reduces carbon emissions and enhances quality of life by lessening energy demand and enhancing environmental sustainability.

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