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Dagar, Vishal and Dagher, Leila and Rao, Amar and Doytch, Nadia and Kagzi, Muneza

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Vishal Dagar, [a,b,] **Leila Dagher,** [c] **Amar Rao,** [d] **Nadia Doytch,** [e,f,g] **Muneza Kagzi** [h]

a Department of Economics and Public Policy, Great Lakes Institute of Management, Gurgaon, Haryana 122413, India

b Centre of Excellence for Sustainable Development (CoE SD) Great Lakes Institute of Management, Gurgaon, Haryana 122413, India

c Lebanese American University, Beirut, Lebanon

d BML Munjal University, 67th KM Stone, NH-8, Gurugram, Haryana-122413, India

e CUNY- Brooklyn College and the Graduate Center, New York, USA

f University of Economics Ho Chi Minh City, Ho Chi Minh City, Vietnam

g Ateneo de Manila University School of Government, Manila, The Philippines

h T A Pai Management Institute, Manipal Academy of Higher Education, Manipal 576104, Karnataka, India

Abstract

Global energy security is a growing worldwide concern in the presence of high economic policy uncertainty (EPU) that can be addressed by advancing sustainable energy diversification (ED) practices. Energy security can be estimated by combining ED and EPU indices; hence, this study uses a dataset covering three continents and 26 countries from 1995 to 2023 to measure energy security employing this approach. The study employs quantile regression and panel data analysis, finding a positive relationship between EPU and ED. The results reveal that when EPU increases, the spectrum of energy sources declines, negatively impacting energy security. Other factors of globalization, Gross Domestic Product, gross capital formation, and the labor force also have an impact on the spectrum of energy sources. To obtain a sustainable level of ED, policymakers should increase investment in gross capital formation because economic growth and openness via pro-global policies have less impact on ED. This study also demonstrates that labor capital shifts have a significant effect on ED. The quantitative results reveal the importance of clear and precise economic policies for increasing investment in carbon-free energy security.

Keywords: Economic Policy Uncertainty; Energy Security; Energy Diversification; Carbon Neutrality; Risk Mitigation.

JEL classification: Q43, Q48, G18, C23, Q54, Q58

1. Introduction

Global economic growth can be accelerated through investment in sustainable energy security. All industrialized economies are dependent on businesses that employ heavy machinery; therefore, understanding countries' energy use systems and advancing consumption efficiency through optimization can increase the benefit for different stakeholders (i.e., industrialists and commercial users, household consumers, and agronomists (Bouoiyour et al., 2019). Energy security refers to a region, state, or country being safe from any unexpected threat of discontinuation in the quantity and quality of energy supply demanded by the population for final consumption in a given time period (Sutrisno et al., 2021). When a country or state achieves this state, it is considered to be energy secure. Energy security is a positive driver of economic growth as it boosts all energy users (Ayoo, 2020; Bran et al., 2012; Farah, 2020; Labandeira & Manzano, 2012). The primary source (petroleum) for energy production seems to be inefficient in meeting current energy security demand, which has been evident in recent crises such as the COVID-19 pandemic and the ongoing unrest in Eastern Europe and the Middle East. Energy sources became unstable as global political uncertainty began to have an impact (Halsnæs & Garg, 2011); therefore, the motivation for this study is to examine the challenge of energy security and understand energy diversification (ED) with policy uncertainties to provide practical insights for advancing sustainable and secure energy.

Normal business cycles are impacted by crises, leading all stakeholders to incur losses and hampering economic growth. Policy uncertainties have been on the rise, encouraging individuals, businesses, and economies to adopt risky, unsustainable energy consumption policies. Ozcan & Ozturk, (2019) found that the cost of natural resources of energy production began to rise due to global disruptions and crises, leading policymakers to opt of policies that were no longer feasible for securing long-term sustainability (Ebhota & Tabakov, 2021). For example, in April 2019, oil-dependent countries were unable to determine the demand for energy because of a sudden oil price fall in the global market (Yuandong et al., 2022).

Global populations have begun to invest in green energy options and adopting approaches to advance energy efficiency and consumption with zero carbon emissions (Zhu et al., 2021) to maintain a balance between demand and supply in the near future (Lee & Wang, 2022). The process of evaluating future energy demand and ensuring adequate supply is called energy security (Abbas & Alqama, 2020). Reducing carbon emissions is also extremely important for attaining worldwide sustainability objectives. Bigerna et al., (2021) argued that reducing the pace of climate change requires focus on advancing clean energy to mitigate the greenhouse effect, which can also be controlled (Selvakkumaran & Limmeechokchai, 2013). The major challenge for energy security is making green energy sources available at lower cost for access and storage (Blum & Legey, 2012).

Economic policy uncertainty (EPU) is a term that describes the uncertainty arising from policies, particularly those related to fiscal and monetary matters that influence the business environment in which firms operate (Pirgaip & Dinçergök, 2020). Uncertainty regarding economic policies impacts investment decisions and rule enforcement, which affects the energy industry considerably. People may be less likely to invest in standard and alternative energy facilities when facing uncertainty regarding potential energy shortages that could put energy security at risk (Y. Zhang et al., 2021).

The cost and quantity of energy can also be affected by changes in economic functioning. Such incidents occur when market actors seek to protect themselves from unknowns that could push prices higher and restrict access to energy (Zakeri et al., 2022). When economic policies change such as during the COVID-19 pandemic or wars in other parts of the world, energy investments may cease, which can threaten supply security and the ability to maintain stable energy sources (Nepal, Best, et al., 2023). The price and availability of energy supplies can change as a result of reduced consumer spending, and policy instability makes it more difficult to shift to renewable energy (Wang et al., 2021). EPU affects traditional energy companies, which subsequently affects investments in renewable energy businesses (Su et al., 2023).

If regulations are robust, green energy sources will be promoted in the long-term, as desired by investors. This is essential to reduce reliance on natural fuels and ensure stable energy supply (Y. Khan et al., 2022). Countries may find it challenging to cooperate concerning energy provision when they are unfamiliar with the rules. Clear regulations are needed to ensure it has sufficient energy power. Uncertainty regarding the government's future policy decisions leads to confusion about economic policy (Pirgaip & Dinçergök, 2020). People wait to buy things, spend money, and produce goods when the cost of risk rises.

Khan et al., (2022) and Amin & Dogan, (2021) revealed a link between increased carbon pollution and uncertainty regarding the economic policies, emphasizing that unclear rules can exacerbate the climate change damage, linking weak economic strategy, high energy use, and carbon dioxide (CO_2) pollution. This has been demonstrated for all member countries of the Organization for Economic Co-operation and Development (OECD) and for G7 countries (Chu, 2022; Chu & Le, 2022; Doğan et al., 2022), where uncertain rules meant to save energy are changed. Studies have also revealed that smog and carbon emissions increase during economic downturns but decrease when clean energy is used (Amin & Dogan, 2021; Adedoyin et al., 2021).

The energy spectrum provides a number of options in terms of the types of available energy sources for consumption. A diverse energy spectrum can improve sustainable energy security in developed economies (Kruyt et al., 2009). Various types of energy produced from different natural or artificial sources can advance energy security while promoting sustainable and eco-friendly sources. Aslani et al., (2012), (2014) examined Finland and Nordic countries respectively, providing compact cases and examples for reducing reliance on high-polluting natural energy sources with the help of power grid energy solutions. These types of environmentally friendly energy spectrums provide more freedom to end users and improve energy security (Nepal, Sofe, et al., 2023). It is essential to understand the available options of the energy spectrum, including natural sources that emit more carbon under higher EPU (Fuss et al., 2012).

A need has emerged to evaluate the alternatives for measuring future energy demand by analyzing energy security; therefore, this study synthesizes the empirical results using ED and EPU variables. To strengthen future policy regimes related to energy markets, this study assesses the cost of risk for advancing sustainable energy consumption patterns after measuring energy security (Pourkhanali et al., 2024). Advancing the availability of a diverse sustainable energy spectrum to support economic activities may reduce the EPU related to fall in energy production (Dagar & Malik, 2023).

This study also examines the role of various macroeconomic drivers using quantitative measures for attaining energy security under EPU, including economic growth (GDP), gross capital formation (GCF), per capita income (PCI), the labor force (LF), and globalization (GLB). This study endeavors to answer the question, how do new energy efficient techniques advance efficient energy spectrum use to address energy security uncertainty? This question constitutes the motivation for this study. In addition, we investigate how these macroeconomic variables impact energy security when facing EPU, proposing the following hypotheses:

H_1: A positive association exists between EPU and ED, wherein increased uncertainty is associated with decreased energy security by diminishing energy sources diversity.

H_2: As reflected in the ED index, economic growth, GCF, the LF, and globalization are significant determinants of energy security, which influence the extent of a nation's ED and energy security.

Our findings, based on quantile regression and panel data analysis demonstrate that EPU has a direct impact on energy security and diversification in the short and long term. The effects of EPU on energy security are also difficult to reverse because they change and vary over time, which intensifies the global call for carbon neutrality (Saud et al., 2018). As a result, achieving energy security and sustainable growth requires stable economic policy for advancing the sustainable energy spectrum. It is easier for people to invest in different types of energy systems in a stable economic and policy atmosphere.

Such stability and certainty also keep things from changing in ways that could interfere with progress toward carbon neutrality. Therefore, policymakers are tasked with ensuring that economic and energy policies are well coordinated, and economic policies make energy policies stronger, promoting less risk to energy security so that the world economy can move toward a low-carbon future. Previous studies have demonstrated that it is essential for economies to balance the need for growth with the need to protect the environment, considering empirical research results (Nepal et al., 2019). Coordinating policies is a crucial aspect of advancing sustainable growth in the real world.

The remainder of this paper is organized as follows. Section 2 provides a review of the relevant literature, Section 3 presents our data and research methodology, and Section 4 reviews the results and discussion, followed by the conclusion and policy recommendations in Section 5.

2. Literature review

Previous studies have revealed a broad shift in the paradigm of energy security. For instance, Aslani et al., (2014) constructed a model for Finland, revealing energy dependency by using a simple causal loop method in the form of a diagram and a systematic dynamic approach. The objective of the study was to showcase renewable energy resources in the form of a portfolio linking the dynamic elements of renewable energy to encourage the development of subsidy packages, increase reliance, and advance sustainable energy consumption. The authors also noted the research gap of energy security-related dynamics in current modeling perspectives. The results revealed a causal loop and related system dynamics in a diagram assessing three Finnish renewable energy policy perspectives from 2020. The findings demonstrated that despite a 7% increase in the total electricity/heat demand in Finland during 2020–2021, the dependency ratio for imported sources can reduce demand by 1%–7%, which is entirely dependent on the policy perspectives and scenarios defined.

Aydin & Esen (2018) showed that energy intensity has a considerable impact on green growth, presenting an innovative, system dynamic panel regression with a threshold for leveraging the normal regression model to examine the threshold effects using an energy intensity variable. The findings showed that energy intensity may accelerate economic green growth in 12

Commonwealth of Independent States (CIS) countries using data from 1991 to 2013 to measure economic growth. The authors referenced Levin et al., (2002), applying a panel regression model, revealing a 0.44% energy threshold, demonstrating that reaching the threshold may significantly reduce economic growth. In addition, when energy usage is lower than the threshold, this may accelerate the economy's sustainable growth. In the context of less energy intensity, policies for advancing a new regime can promote significant growth only when combined with an efficient economic policy for energy intensity.

Rasoulinezhad & Saboori, (2018) revealed a strong linkage between energy use and composite trade intensity (CTI) using the Chinn–Ito index for CIS countries, introducing CTI countries and the index for the first time in combined pollution framework in an economic context (Chinn & Ito, 2008). The findings revealed long-term, two-way correlations between all variables in the model including all 12 CIS nations, other than those between growth perspectives and recycled energy consumption. In the study, the authors constructed a three-panel regression model comprising unit root tests and panel cointegration, verifying causality using two panels referencing Im et al., (2003). The short-term panel causality tests confirmed a one-way link between growth perspectives, globalization in terms of financial investment, CO_2 emissions, and energy consumption.

Apergis & Payne (2009) presented a model using a multivariate panel dataset to examine the impact of energy consumption and green growth perspectives in 11 CIS countries from 1991 to 2005. The results confirmed that the theory of energy consumption is positively correlated with sustainable growth (Pedroni, 2001, 2004) examining the differences between energy use and PCI. Another study by Narayan and Doytch (2017) concluded that the renewable energy drivers of growth are only effective in developing countries, while non-renewable energy drivers support growth and the conservative hypotheses.

While a number of studies on carbon emissions have been conducted, as of now, the nexus of energy use and climate change due to carbon emissions has not been thoroughly investigated using EPU (Amin & Dogan, 2021). Some research related to EPU, and the environment has shown a high level of flexibility in results. For example, Amin & Dogan (2021) demonstrated the dynamics of China's environment and EPU. The results of another study showed that renewable energy reduces emissions, and income and energy intensity increase emissions (Doytch & Narayan, 2021).

Ambiguity exists regarding government policies in the case of EPU, which can increase pollution through uninformed actions under circumstances of policy deficiency. The outcomes of previous research have demonstrated an alignment among the United Nations Sustainable Development Goals (SDG) and government policies related to the environment and climate actions to advance sustainability. For example, Odhiambo, (2009) examined energy use and EPU to provide insights regarding climate change and environmental degradation, revealing similar output impact from policy implications using a pooled dataset of 22 OECD countries from 1985 to 2017to measure a mean group autoregressive distributed lag model.

Energy security ensures expedient and safe energy access. Modern economies require a reliable and smooth energy supply (Abbas & Alqama, 2020), which enhances the connection between energy and citizen security as an important source of growth. Fears stem from the 1973 oil embargo, which prompted large economies to consider energy security more seriously. Abbas & Alqama (2020) demonstrated correlations between energy, sustainable growth, and citizen security. Concerns regarding energy, sustainable growth fomented a national security paradigm shift (Dabboussi & Abid, 2022), indicating that political and economic elements sparked a worldwide debate on energy and national security.

Ikram et al., (2021) addressed a research gap by examining Pakistan's key green technology attributes, identifying eight leading indicators pertaining to green technology using the fuzzy analytical hierarchy process to prioritize primary and sub-primary indicators. The results indicated that the supply chain, green energy, and agriculture were the most significant of the 43 sub-criteria tested. Moreover, green technology is a significant driver of cleaner manufacturing and sustainable growth investment (Salari et al., 2021).

Ha & Thanh (2022) examined the dynamic relationship between global value chains (GVCs) involvement using seven indicators to measure energy security by focusing on sustainability. The study determined cointegration for time-series data available to bridge GVCs and energy security performance (ESP) to validate the effects. The findings also indicated that the relationship between GVC and ESP variables is skewed, which is more prominent for high-income economies. Similar results were found when examining backward and forward links of GVCs' involvement on ESP.

Sharifuddin (2014) presented a quantitative energy security evaluation. Lack of data for southeast Asian countries, caused the investigator to use a modified procedure, dividing the model for energy security into 5 main parts and 13 subparts and measuring the 13 factors using 35 indicators. Pavlović et al. (2018) constructed a comprehensive composite index (CI), of energy security indicators for natural gas supply, including normalized indicator values and weighted components. The findings of this study show that the higher composite index value represent low level of consumption of natural resources of energy due to the low level of supply of the same to preserve them. Data regarding Croatia's reserves to measure the natural gas supply covered 2001–2015. The CI peaked at 0.58 in 2001 and dropped to 0.37 in 2015, indicating that Croatia's natural gas supply security has improved over time. In addition, a functional liquefied natural gas facility on Krk island in the North Adriatic boosted the CI to 0.30 in 2019, meaning that gas supply security in Croatia improved dramatically in 2019.

Energy supply and energy use were identified to examine energy security in China. Since China was a net crude oil importer in 1996 (Wu et al., 2012). Since that year, China has increased investment in environmental policies and to promote regional energy security concerns. Wu et al. (2012) investigated how China's need for energy security evolved and whether climate-related regulations have affected China's need for energy security. The study revealed shifts in China's need for energy supply and energy security from 1996 to 2009, growing considerably from 1996 to 2001, decreasing rapidly from 2002 to 2005, and falling moderately from 2006 to 2009. China's energy security index rose from 1996 to2002, declined from 2003 to 2005, and rose from 2006 to 2009. China's energy-saving and emissions reduction program has reduced energy supply security and considerably improved energy use security, leading its CI to present an inverted U-shaped pattern (Narayan & Doytch, 2017).

The Paris Climate Agreement targeting no more than 1.5°C global warming by 2100 promoted campaigns at national, sub-national, and commercial levels to encourage economic activities with net-zero CO_2 emissions goals (Shakya et al., 2023). At the same time, economic growth in developing countries has accelerated, benefiting socioeconomic welfare and climate resilience while making it impossible to attain net-zero emissions. There are many approaches for achieving net-zero emissions, climate resilience, and sustainability, and promoting public education and research related to net-zero emissions is extremely beneficial. Such programs may encourage collaboration between developed and developing countries to advance attaining the net-zero emissions target.

Shakya et al. (2023) employed a LEAP analysis to measure Nepal's long-term planning for achieving net-zero emissions with environmental, energy security (renewable and non-renewable sources), and energy equity variables. The findings projected that CO_2 emissions will rise from 23 to 79 MtCO2 from 2019 to 2050. The quantity of air pollution emissions will surge from 60% to 183%, increased energy use may accelerate the rate of import dependency, and per capita electricity usage will decrease by 25% of the world average.

Although many energy security models have been proposed, only a few are globally accepted as having valid metrics and units. International bodies related to energy agencies have largely agreed on a similar definition of energy security providing a dynamic measure through systems analysis, yielding three important energy security indicators and a progressive approach to examine the process-flow of the energy security systems model. The details of this model were examined by Hughes (2012). The energy use model is used to promote energy transformation to achieve the average household demand. Analysis of energy security uses indicator-specific metrics for energy use, energy demand, and environmental degradation, to determine each process in the flow of energy and measure energy security.

New approaches have been employed in contemporary research to advance low-carbon energy consumption and ensure energy security and are being supported for achieving the SDGs. The question of using technology to improve non-renewable energy efficiency with sources, energy markets, and economic expansion will considerably impact energy security in the next century. Metrics for maintaining energy security in Europe are based on sovereignty, economic policy stability, robustness, and resilience were proposed by Guivarch & Monjon (2017) using uncertainty regarding energy related system drivers such as government regulations.

A comparison of energy security indicators from different policy perspectives can be used to determine the effect of policies with the high level of volatility or unexpected economic growth. Therefore, our analysis includes variance while also considering each factors' contribution requires consideration of EPU. In addition, the data used for measuring energy intensity in Europe may have some issues lowering CO_2 emissions. Energy security could provide a lot of options that could help low-carbon emitting societies to adopt energy security methods. These are perspectives of low-carbon energy production for measuring the economic policy indicator and uncertainty. Power electronic systems' resilience improves with energy efficiency, and such strategies can diminish climate policy and energy security risks.

3. Data and methodology

3.1.Data

This study uses a database with annual data covering 1995 to 2023 to examine the economic development in 26 nations with different EPU and energy consumption patterns. The regions and countries in the dataset include Asia is represented by China, India, Japan, South Korea, and Singapore; Europe, represented by Belgium, Croatia, Denmark, France, Germany, Greece, Ireland, Italy, the Netherlands, Russian Federation, Spain, Sweden, and the United Kingdom; North America (Canada, Mexico, and the United States); Oceania, represented by Australia, and New Zealand; and South America, represented by Brazil, Chile, and Colombia.

The focus of this study is the unique independent variable of EPU, which is estimated using newspaper and social media platforms covering news and information. The values of our EPU index reveal specific opportunities for advancing scientifically informed economic decision making strength. The control variables in our model include GDP, which is a critical variable in energy studies because it reflects a country's economic health and activity.

Studies have shown a strong association between energy consumption and economic development. For instance, Yu, Huang, and Huarng, (2016) noted that GDP reveals correlations between energy consumption and economic development. Furthermore, Oh & Lee, (2004) and Stern, (2000) identified a bidirectional causal relationship between energy and GDP, making it a relevant control variable for ED studies. GCF impacts environmental efficiency and emissions that are key factors of ED. Hsieh et al., (2019) found that GCF significantly affects environmental efficiency and emissions. Encinas-Ferrer & Villegas-Zermeño, (2018) emphasized GCF's role in expanding productive capacity and long-term economic growth, which is relevant for energy studies. LF influences the economy and individual workers' consumption, affecting energy consumption patterns.

Ben-Porath, (1973) and Bruns, König, and Stern, (2019) highlighted LF participation as a significant factor in energy studies as it impacts wages and income. GLB affects energy consumption patterns and is essential for understanding energy security. Zhang et al., (2023) found that GLB is positively correlated with electricity production and energy consumption. Kasaei, Gandomkar, and Nikoukar, (2017) emphasized the significance of GLB for advancing the penetration and adoption of renewable energy sources and concerns about global warming, which are critical in energy security studies.

The data for GDP, GCF, LF, and GLB are obtained from the World Bank's World Development Indicators database. Our EPU data are obtained from the Economic Policy Uncertainty Index website, which compiles indices for different countries based on respective EPU. All variables are adjusted to a natural logarithm form to normalize the data and reduce the influence of outliers.

The panel data model employed in this study accounts for country-specific effects and temporal dynamics, allowing for nuanced analyses of the relationships between EPU and ED across different national contexts. The comprehensive coverage of our dataset over nearly three decades provides a robust foundation for examining the long-term effects of EPU on energy security. This period includes several significant global events that have impacted economic policies and energy markets, making it an ideal timeframe for our study.

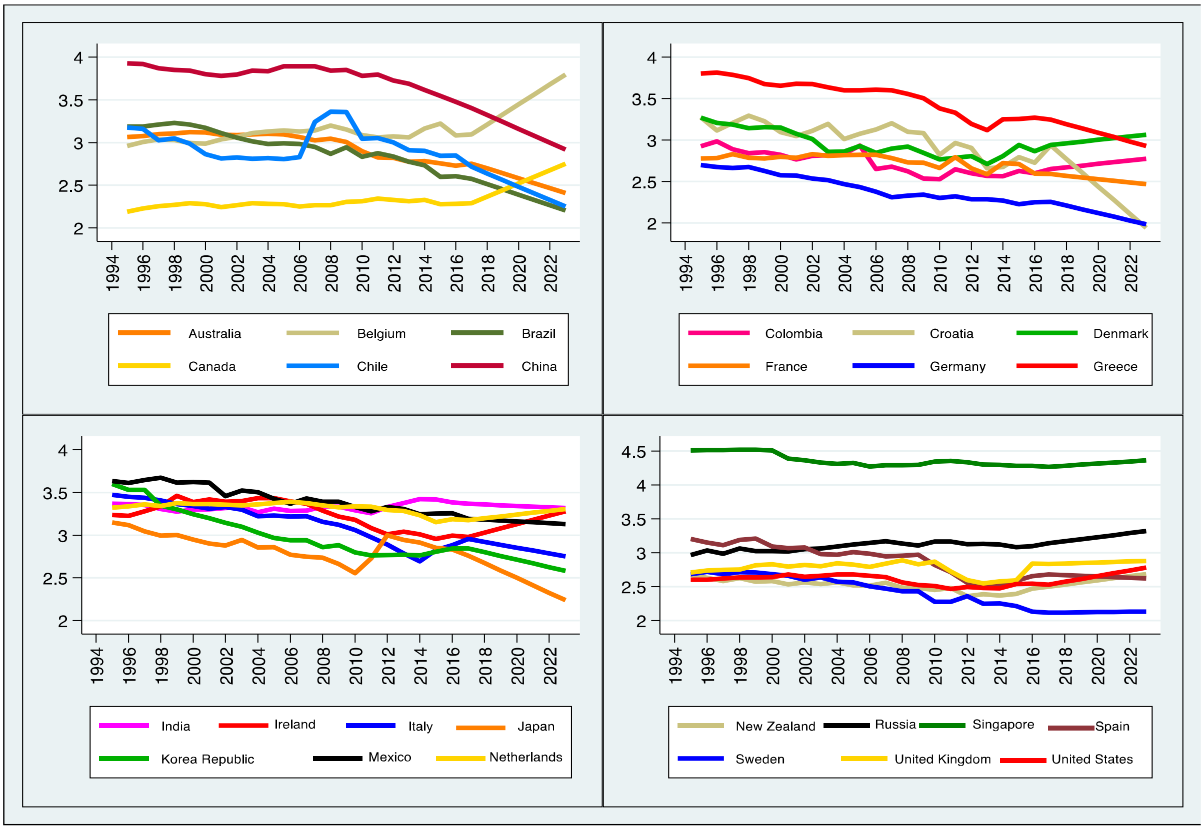
3.2.Methodology

This study investigates the impact of EPU on energy security using panel estimation methods as these techniques are superior to cross-sectional and time-series data (Kumari & Sharma, 2017). The base model for this study as follows:

$$ED_{it} = f(EPU_{it}, GDP_{it}, GCF_{it}, LF_{it}, GLB_{it}, EMISSION_{it}) \quad (1)$$

where t represents the sample period (1995–2023), ED represents the dependent variable (energy diversification), EPU represents the key independent variable of interest, and GDP, GCF, LGF, GLB, $EMISSION$ are control variables. Figure 1 presents the trajectory of ED from 1995 to 2023 for the selected countries from different continents.

Figure 1. Energy diversification over years-all countries



Sources: Authors estimates from Statistical Review of World Energy dataset of British Petroleum (1995-2023)

We use PCI in the later stage of analysis to test the robustness of our model. Taking the log of equation (2) on both sides, the model stands as follows:

$$ED_{it} = \beta_0 + \beta_1 EPU_{it} + \beta_2 GDP_{it} + \beta_3 GCF_{it} + \beta_4 LF_{it} + \beta_5 GLB_{it} + \beta_6 EMISSION_{it} + \varepsilon_{tt} \quad (2)$$

We take the log to mitigate the issue of heteroskedasticity (Saidmamatov et al., 2023).

$$lnED_{it} = \beta_0 + \beta_1 lnEPU_{it} + \beta_2 lnGDP_{it} + \beta_3 lnGCF_{it} + \beta_4 lnLF_{it} + \beta_5 lnGLB_{it} + \beta_6 lnEMISSION_{it} + \varepsilon_{tt} \quad (3)$$

Dynamic panel data methods are used to address endogeneity issues for non-time-varying variables for the different countries (Yerdelen Tatoglu & Gul, 2020). We applied the dynamic panel regression model to resolve time lag issues, Arellano and Bond, (1991). Reducing the fixed effect values for individual countries enables us to introduce changes in the regression method into the baseline approach (Blundell & Bond, 1998) using methods of comparing the reducing fixed effect has an instrumental variable to resolve issues of reducing the value of error term and endogeneity between the variables (Bond, 1991). These techniques have been used in previous studies to present significant regression results (Arellano & Bover, 1995). We adopt a system generalized method of moments (GMM), as follows:

$$y_{it} = \sum_{j=1}^{p} \alpha_j y_{i,t-j} + x_{it}\beta_1 + w_{it}\beta_2 + v_i + \epsilon_{it} \; i = 1, \ldots, N t = 1, \ldots, T \quad (4)$$

In contrast to alternative techniques, the system GMM also demonstrates superior performance, as observed in studies such as Bond, (1991), who demonstrated that the method outperforms other GMM estimators that have been shown to potentially yield biased and imprecise estimates (Arellano & Bover, 1995). Due to its numerous benefits and extensive range of capabilities, we use the system GMM estimation approach as the preferred method for performing dynamic panel data analysis referencing Blundell & Bond, (1998).

For the key estimation, we employ the simple quantile regression method proposed by (Machado & Silva, 2019) with fixed effects. This method is robust to the presence of data outliers and avoids considering possible heterogeneity across individual units in panel data that are unobserved. The simple quantile regression helps to determine ED values concerning similar cases that may differ in similar moments under fixed effects. The value of the parameters with random effects for each country may change for those that fall under each quantile with the change in the summary statistics similar to the cases (Canay, 2011; Koenker, 2004) and others QY(τ|X) for the model of a particular feature.

$$Y_{it} = \alpha_i + X_{it}'\beta + (\delta_i + Z_{it}'\gamma)U_{it} \quad (5)$$

where the value of $\mathrm{P}\{\delta_i + Z_{it}'\gamma > 0\} = 1.(\alpha, \beta', \delta, \gamma')'$ represents the probability of undetermined parameters. $(\alpha_i, \delta_i), i = 1, \dots, n$, with a fixed effect indicates the impact on time period i, and Z is a k-vector of X determined parameters that can be used in place of l, which is obtained as follows:

$$Z_l = Z_l(X), l = 1, \dots, k \quad (6)$$

For any other random or fixed effects, i and X_{it} are distributed with the same proposition and are independent (random) for the time period (t). U_{it} has a possibility of being randomly allocated among individual countries (i) over the time (t) and bidirectional to X_{it}, which helps satisfy the condition for significance (Machado & Silva, 2019) as exogeneity is not evident among the variables considered. The following equation represents the same:

$$Q_Y(\tau|X_{it}) = \big(\alpha_i + \delta_i q(\tau)\big) + X_{it}'\beta + Z_{it}'\gamma q(\tau) \quad (7)$$

where X_{it}' is a possible distribution for exogenous outcomes, after considering the logarithmic values of the study's variables. $Q_Y(\tau|X_{it})$ represents the unidirectional (random) distribution for the variables included in the endogenous variable Y_{it} (natural log value of EPU is considered), which has a possible requisition for the variables on the right side of the equation (X_{it}). $\alpha_i(\tau) \equiv \alpha_i + \delta_i q(\tau)$ measures the effect for each quantile $(-\tau)$ for each country that may be stagnant with i.

Change in the slope of the intercept cannot be revealed using this technique as the method does not support simple least squares (Hansen, 1999). The impact over time can be determined using the values of the variables that may impact internal variables' value in different quantiles with specific input variable change (Y). $q(\tau)$ shows that $\tau - th$ may be applicable for maximizing the fixed effects issue in each quantile to reduce the error term's value.

$$min_q \sum_i \sum_t \rho_\tau(R_{it} - (\delta_i + Z_{it}'\gamma)q) \quad (8)$$

where $\rho_\tau(A) = (\tau - 1)AI\{A \leqslant 0\} + TAI\{A > O\}$ determines the identified relationship.

3.2.1 Energy diversification index

Referencing the methodology adopted by (Gozgor and Paramati, 2022), we extend the ED index to 2023.

$$\frac{\sum_{j=1}^{n_i}\left(\frac{x_{it}}{X_{it}}\right)^2-\frac{1}{n_i}}{1-\frac{1}{n_i}} \quad (9)$$

We employ the Herfindahl–Hirschman index (Chang et al., 2023; S. J. Kim & Kim, 2023; Y. J. Kim, 2022), which was originally used to measure export market diversification as outlined by the World Bank in 2013, to quantify energy source diversification in all selected countries. For detailed information, please refer to Gozgor and Paramati (2022). Table 1 shows the details related to all considered variables, such as symbols, units, and sources.

Table 1. Variables

Symbol	Variable	Unit	Source
Dependent variable			
ED	Energy diversification index	Index	(Gozgor & Paramati, 2022)
Independent variable			
EPU	Economic policy uncertainty	Index	(Baker et al., 2016)
Control variables			
GDP	Gross domestic product	constant 2010 US$	World Bank (2023)
GCF	Gross capital formation	constant 2010 US$	World Bank (2023)
LF	Labor force	Count	World Bank (2023)
GLB	Globalization	KOF Global index	(Gygli et al., 2019)
PCI	Per Capita Income	constant 2010 US$	World Bank (2023)
EMISSION	CO2 unit energy per annum	kg per kilowatt per hour	Our World in Data (2023)

Sources: Statistical Review of World Energy dataset of British Petroleum (1995-2023) and World Development Indicators (1995-2023) of World Bank.

Notes: ED = log of Energy diversification index; EPU = log of Economic policy uncertainty; GDP = log of Gross domestic product; GCF = log of gross capital formation; GLB = log of globalization index; PCI = log of Per Capita Income; EMISSION = log of annual CO2 emissions per unit energy. Observations (Overall: N = 754, between n = 26, within T = 29).

4. Empirical results and discussion

4.1.Empirical results

We next present a thorough examination of the results and outcomes derived from the experiments and analyses of this study, simultaneously comparing our findings to the existing body of knowledge within the pertinent literature. The discussion then explores the implications of the findings, their relevance to the broader field, and their capacity to enhance our understanding of the subject matter.

Table 2 presents a summary of statistics for developing our econometric models. The mean, median, maximum, minimum, standard deviation, skewness, kurtosis, and Jarque–Bera provide insights for the 754 observations of ED, EPU, GDP, GCF, LF, GLB, emissions, and PCI.

Table 2. Descriptive statistics

	ED	EPU	GDP	GCF	LF	GLB	EMISSION	PCI
Mean	2.984	4.747	13.719	12.239	2.938	4.324	0.191	10.066
Median	2.953	4.752	13.864	12.447	3.089	4.374	0.196	10.489
Maximum	4.519	6.674	16.845	15.717	6.666	4.528	0.324	11.577
Minimum	1.942	1.707	10.592	8.740	0.436	3.677	0.032	6.5154
Std. Dev.	0.474	0.561	1.305	1.370	1.587	0.158	0.055	0.97
Skewness	0.774	-0.428	-0.015	0.025	0.451	-1.254	-0.330	-1.44
Kurtosis	4.021	6.413	2.620	2.656	2.623	4.206	3.086	4.775
Jarque-Bera	107.95	389.050	4.568	3.793	29.987	243.438	13.948	360.51
N	754	754	754	754	754	754	754	754

Sources: Authors estimates from secondary data of Statistical Review of World Energy dataset of British Petroleum (1995-2023) and World Development Indicators (1995-2023) of World Bank.

Notes: ED = log of Energy diversification index; EPU = log of Economic policy uncertainty; GDP = log of Gross domestic product; GCF = log of gross capital formation; GLB = log of globalization index; EMISSION = log of annual CO2 emissions per unit energy; Observations (Overall: N = 754, between n = 26, within T = 29).

Table 3 shows the estimations of our panel quantile regression exploring the nonlinear relationship between ED (dependent variable) and EPU (independent variable) and control variables (GDP, GCF, LF, GLB, PCI, and EMISSION). The coefficient of GDP shows a dual relationship with ED, wherein the relationship is positive at lower quantiles (Q10–Q50; 1.919–0.782, respectively), indicating that ED tends to increase with an increase in GDP; however, from Q70 to Q90, the coefficients become negative, with a maximum magnitude of −1.793 at the extreme quantile (Q90). EPU estimates reveal a negative relationship between GDP and ED due to economies of scale.

The coefficients of GCF maintain a positive and consistent relationship with ED, although the magnitude increases to 0.712 at higher quantiles, indicating a significant influence of GCF in directing ED (Udemba et al., 2023). LF shows a consistently negative relationship with ED across all distributions, indicating that a large LF can lead to a more concentrated mix of energy sources. GLB has a negative association with ED, with a magnitude of coefficients from −1.491 to −1.138, suggesting that global market dynamics may favor less diversification. The estimations reveal heterogenous impact as the coefficients of PCI show a negative relationship at lower quantiles, but the relationship turns positive when moving to higher quantiles (Q80–Q90).

At the beginning of the quantiles (i.e., 0.1), a higher ED level is revealed with a marginal gain in income, and in higher quantiles (i.e., 0.9), a lower ED level is revealed with an increase in income. A positive correlation is evident between emissions and ED in lower quantiles that turns negative at upper quantiles (Q90; −1.201). The study's key variable (EPU) has a significantly positive association with ED at extreme quantiles (Q0.8–Q0.9), with magnitudes of 0.0996 and 0.135, respectively. In some selected countries EPU may bounce back and decrease sustainable growth.

Some policymakers opt for short-term flexible plans to manage the risks associated with EPU as increased uncertainty can make firms and policymakers unable to afford the negative impact of shifting from energy spectrums with no guarantee of covering the risk of opting for other energy market solutions. Rahman & Ahmad (2019) demonstrated a circumstance in which CO_2 emissions are positively correlated to GCF. Finally, the coefficients of EPU range from −0.123 at Q1 to 0.198 at Q9, revealing a significant positive correlation from Q6 onward.

Table 3. Quantile regression estimates

	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90
GDP	1.919*** (7.06)	1.511*** (6.42)	0.997** (3.18)	0.840*** (3.95)	0.782* (2.53)	0.328 (0.98)	-0.0678 (-0.17)	-1.482*** (-4.17)	-1.793*** (-17.04)
GCF	0.371** (2.82)	0.244* (2.21)	0.241** (3.10)	0.242*** (3.40)	0.190* (2.42)	0.132 (1.57)	0.289*** (4.02)	0.550*** (4.24)	0.712*** (15.19)
LF	-2.340*** (-8.79)	-1.807*** (-6.92)	-1.301*** (-4.32)	-1.144*** (-5.21)	-1.036*** (-3.49)	-0.554* (-1.97)	-0.353 (-1.02)	0.702** (3.04)	0.812*** (8.46)
GLB	-1.491*** (-5.23)	-0.931** (-3.24)	-0.547** (-2.62)	-0.523* (-2.36)	-0.526* (-2.08)	-0.674* (-2.42)	-0.548** (-3.10)	-0.595** (-2.85)	-1.138*** (-7.52)
PCI	-2.060*** (-9.47)	-1.652*** (-7.69)	-1.215*** (-4.62)	-1.061*** (-5.56)	-0.966*** (-3.63)	-0.512* (-2.06)	-0.373 (-1.14)	0.668** (2.83)	0.811*** (9.09)
EMISSION	2.501*** (7.35)	3.059*** (8.94)	3.568*** (16.42)	3.337*** (9.86)	2.799*** (8.81)	2.825*** (8.01)	2.501*** (4.11)	1.097 (1.34)	-1.201*** (-3.86)
EPU	-0.0183 (- 0.67)	0.0157 (0.80)	0.0266 (1.43)	0.0152 (0.56)	0.0124 (0.48)	0.0522 (1.56)	0.0586 (1.95)	0.0996*** (3.60)	0.135*** (4.41)
_cons	5.360*** (7.85)	4.256*** (5.16)	3.725*** (6.20)	3.921*** (5.58)	4.303*** (4.40)	5.807*** (5.94)	6.939*** (9.11)	10.05*** (8.10)	13.40*** (18.93)

Sources: Authors estimates from secondary data of Statistical Review of World Energy dataset of British Petroleum (1995-2023) and World Development Indicators (2023) of World Bank.
Notes: ED = log of Energy diversification index; EPU = log of Economic policy uncertainty; GDP = log of Gross domestic product; GCF = log of gross capital formation; GLB = log of globalization index; EMISSION = log of annual CO2 emissions per unit energy; N= 754; t statistics in parentheses; * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Conversely, a significant positive correlation emerges in higher quantiles, indicating that EPU may paradoxically drive economies toward a concentrated energy sector (Mišík, 2022). This could be interpreted as a strategic move to mitigate the risks associated with policy volatility, wherein economies opt for energy consolidation as a form of security against flexible policy. Liu et al. (2020) found that policy instability impacts energy producers, causing a pragmatic shift in investment, demonstrating the necessary conditions of diversification by relaxing the concept of policy instability. Hemrit & Benlagha (2021) suggested that the renewable energy index shows lower values due to high level of policy instability in initial quantiles, indicating a potential constraint on growth or diversification in certain energy sectors. Assaf et al. (2021) emphasized the significant influence of energy market dynamics on EPU, including aspects of diversification (Dagher et al., 2023).

4.2. Discussion

Our findings support hypothesis H_1 regarding the impact of EPU in energy security policies with a diverse set of energy sources, based on the estimates from quantile and panel data considering ED as a dependent variable for EPU. PCI is considered an exogenous variable in the model. Table 4 presents the panel data estimates using Arellano–Bond and system GMM methodologies, revealing the unidentified dynamics of ED with macroeconomic and environmental pollution indicators (Rao et al., 2023). Autocorrelation values are significant after considering ED in both models, revealing presence of ED in the long-term.

Table 4. Dynamic Panel data estimation results

	Arellano–Bond estimation	Panel estimation
ED_1	0.007*** (0.001)	0.009*** (0.001)
GDP	-0.552*** (0.005)	-0.736*** (0.006)
GCF	0.413*** (0.006)	0.520*** (0.008)
LF	0.042*** (0.003)	0.106*** (0.006)
GLB	-0.170*** (0.020)	0.191*** (0.323)
EMISSION	1.306*** (0.021)	0.955*** (0.025)
EPU	0.090*** (0.007)	0.125*** (0.008)
CONS	5.422*** (0.069)	4.777*** (0.103)

Sources: Authors estimates from secondary data of Statistical Review of World Energy dataset of British Petroleum (1995-2023) and World Development Indicators (1995-2023) of World Bank.

Notes: ED = log of Energy diversification index; EPU = log of Economic policy uncertainty; GDP = log of Gross domestic product; GCF = log of gross capital formation; GLB = log of globalization index; EMISSION = log of annual CO2 emissions per unit energy; ***p-value≤1%, **p-value≤5%, *p-value≤10%.

The results show that an increase in GDP decreases the adoption of ED. H_2 is also accepted based on the negative relationship revealed between these two factors, which helps in defining the role of EPU and its vital role for estimating energy insecurity while increasing GDP. GCF may also positively increase energy security with increased ED. The complexity of these system dynamics reveals that the majority of policy certainty can be driven by increasing investment in capital intensive energy spectrums.

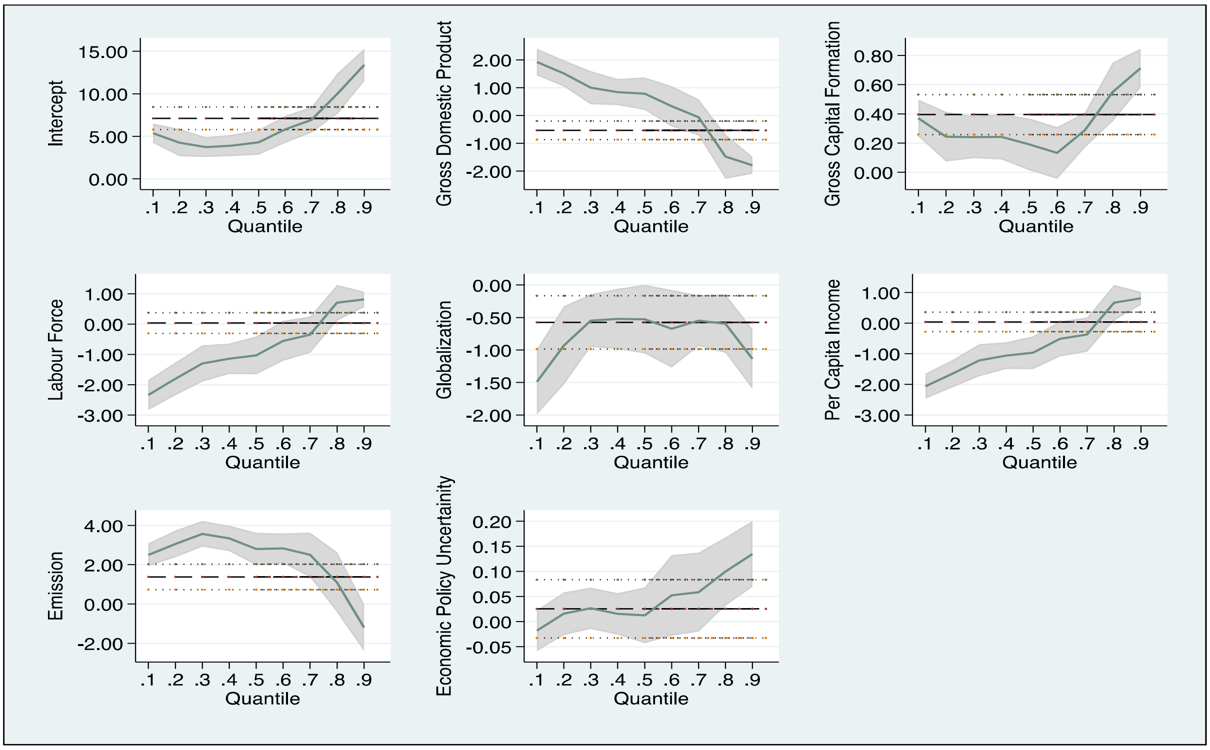
Emir & Bekun (2019) presented the causality dynamics for confirming the links between economic growth and energy intensity focusing on ED. (Dagher et al., 2017) confirmed this finding in another study that considered environmental sustainability as a crucial factor for advancing ED using the available energy spectrum. Similarly, Apergis & Payne (2009) examined the long-term, two-way causality between energy, growth, and environmental degradation.

The positive value of the coefficients for the LF across both models (Arellano–Bond: 0.042; system GMM: 0.106), shows that as various energy production-related techniques come are adopted, a large proportion of the population becomes more energy efficient and opt for further ED. The negative values of the GLB coefficient (Arellano–Bond: −0.170; system GMM: 0.191) reveal a negative relationship between ED and GLB due to stringent international policy.

The positive coefficient of emissions (Arellano–Bond: 1.306; system GMM: 0.955) indicates that higher emissions promote more ED (Dagher et al., 2020). This positive relationship could depict a perspective in which plans for ED include increased emissions and for more inefficient energy sources such as natural fuel, petroleum, oil, and gas. The various coefficient estimates for EPU across different quantiles highlight the heterogeneous effects of EPU on ED. At lower quantiles, where the distribution is skewed toward economies experiencing relatively lower EPU, the coefficients tend to be negative but statistically insignificant.

Figure 2 provides quantile regression estimations that illustrate the movement of the coefficient for ED over the years in each quantile. The findings suggest that the impact on ED may be limited in more stable economic environments that are characterized by lower EPU.

Figure 2. Quantile regression estimation



Sources: Authors estimates from secondary data of Statistical Review of World Energy dataset of British Petroleum (1995-2023) and World Development Indicators (1995-2023) of World Bank.

Conversely, the coefficient estimates for EPU become increasingly positive and statistically significant when moving toward higher quantiles, representing economies facing greater EPU.

This indicates that environments marked by heightened EPU have a stronger propensity toward increased ED. This finding of this study is consistent with economic theory, which posits that uncertainty can act as a catalyst for diversification as firms and households seek to hedge against the potential risks associated with policy volatility.

In the context of energy markets, elevated EPU may lead to higher investments in a diverse range of energy sources, thereby enhancing energy security and resilience to policy shocks. Furthermore, the positive relationship between EPU and ED underscores the influence of policy stability and clarity in shaping energy transition pathways. EPU can disrupt long-term planning and investment strategies, potentially hindering the adoption of cleaner and more sustainable energy technologies.

5. Conclusion and policy recommendations

This study investigates the significance of ED in composing the economic growth introducing EPU and energy security to achieve the SDGs. The results reveal that during the take off stage of economic growth most economies are prone to use non-renewable energy sources as EPU influences a state’s budgetary structure, which compromises energy security. In the long-term, tax discounts or encouraging public savings for adopting renewable energy sources can cultivate a positive relationship between GCF (as savings can be converted to further investment in renewable energy sources) and ED to protect energy security.

The working population is a significant driver of ED as they are more likely to invest in diversified energy sources, including renewables. In contrast, GLB presents a challenge to ED as compliance with international policies can increase the costs and complexity of adopting sustainable energy practices. Our study also reveals that economies with higher emissions are more inclined to diversify energy sources, including renewable and non-renewable sources. This diversification is driven by the need to balance energy security with environmental sustainability. Drawing insights from our results and conclusion, the positive relationship between GDP and ED at lower quantiles suggests that economic growth initially supports ED; however, the negative relationship at higher quantiles indicates that further economic growth beyond a certain threshold may lead to less diversification, which is possibly attributable to increased reliance on specific energy sources.

5.1. Theoretical policy implications

Policies for advancing sustainable energy consumption to attain balanced economic growth with ED can be developed based on the findings of this study. The positive relationship between ED and GCF revealed in the quantile analysis indicates that further investment is required to establish the infrastructure for producing sustainable energy. Better solutions can be promoted to attract private and public investments to produce renewable energy and more efficient technologies to achieve energy security through ED. The quantile analysis illustrates a complex relationship between ED and the LF, in which lower quantiles have a negative relationship, and higher quantiles have a positive relationship.

The trend suggests that in the early phases, the mass workforce population is focused on multiple types of energy, but may later opt for ED. More policy initiatives should be implemented to develop relevant skills among the LF by providing training and educational opportunities. The same pattern is evident regarding a relationship between GLB and ED in the lower and upper quantiles, with a negative relationship in the lower quantiles that gradually starts becoming positive as the gestation period for adopting new technologies progresses due to international collaboration.

The focus of international bodies, i.e., the International Monetary Fund and the World Bank are under the direct oversight of United Nations to ensure the global efforts with an increase in international cooperation should promote the exchange of technologies to produce renewable energy. The trend in the lower to upper quantiles for PCI and ED is also negative to positive. Like GLB, the impact of increased PCI tends to positively affect ED in the later stage of income saturation. New policy tools should be developed to increase investment for promoting a diverse renewable energy spectrum with increased income.

A different trend is revealed for most of the quantiles for emissions and ED, showing a positive relationship between emissions and ED as most of the developing countries that contribute the most emissions are shifting toward diverse renewable energy sources to reduce pollution. Therefore, the developing world is growing faster in terms of advancing diverse renewable energy sources to navigate present environmental challenges.

5.2.Managerial policy implications

Economies with standard incentive schemes and pro-environmental norms and regulations are more likely to promote diverse renewable energy sources; therefore, these incentives and regulations can be recommended to other economies to promote adoption of ED policies. The relationship between EPU and ED is found to be positive in the upper quantiles, indicating that economies are concerned about the development of better disaster and risk management policies. Stable, long-term policy frameworks of developed and developing economies regarding certain standard practices can be considered an active initiative in the direction of mitigating the risk attached to short-term energy security-related EPU.

In short, the focus of the governments and international cooperation should be to develop a resilient and environmentally friendly diverse renewable energy portfolio to provide a secure energy secure future for generations to come with the following measures. Develop long term, stable energy policy to encourage ED. Identify and promote the drivers for promoting diverse renewable energy sources. Develop resilient, energy secure systems with better regulations and infrastructure. Encourage investment in incentivized systems to advance the adoption of more renewable ED. Promote energy transition with rapid and efficient techniques for advancing a diversified energy mix. Promote public–private collaboration to boost international cooperation. Develop funds for disaster and risk management to mitigate potential energy security crises. Investors and energy producers should be cultivated with liberal economic and financial policy frameworks to hedge from volatility sentiment and facilitate a shift in the paradigm. Finally, more resilient strategy frameworks should be developed to avoid dependency on non-renewable sources of energy production.

Policymakers and various stakeholders should focus on the macroeconomic circumstances to balance the consumption and production of sustainable and renewable energy by encouraging savings and investments for advancing diversified renewable energy sources. Furthermore, long-term policy frameworks can be developed to encourage the allocation, distribution, and stabilization of new clean technologies and diversified renewable energy sources. More incentive schemes can be introduced into existing systems to promote the practices of ED. Such schemes can be in the form of tax discounts, subsidies for adopting renewable energy solutions, and grants or funds for innovative schemes and technologies. Promoting research and development in ED for providing energy security can cover the potential EPU risk.

Declaration of Competing Interest

Authors have no competing or conflict of interest with any party. Also, authors declares that they do not have any financial or non-financial conflict with any party who are directly or indirectly related to this study.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used paperpal.ai in order to improve the language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Appendix

A1: Quantile regression

Quantile	ed	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
Q10	gdp	1.919	0.272	7.06	0	1.386	2.453	***
Q10	gcf	0.371	0.131	2.82	0.005	0.113	0.629	***
Q10	lf	-2.34	0.266	-8.79	0	-2.862	-1.817	***
Q10	glb	-1.491	0.285	-5.23	0	-2.051	-0.932	***
Q10	pci	-2.06	0.217	-9.47	0	-2.487	-1.633	***
Q10	emission	2.501	0.34	7.35	0	1.832	3.169	***
Q10	epu	-0.018	0.027	-0.67	0.504	-0.072	0.035	
Q10	Constant	5.36	0.682	7.85	0	4.02	6.699	***
Q20	gdp	1.511	0.235	6.42	0	1.049	1.973	***
Q20	gcf	0.244	0.11	2.21	0.027	0.028	0.46	**
Q20	lf	-1.807	0.261	-6.92	0	-2.32	-1.294	***
Q20	glb	-0.931	0.287	-3.24	0.001	-1.494	-0.367	***
Q20	pci	-1.652	0.215	-7.69	0	-2.073	-1.23	***
Q20	emission	3.059	0.342	8.94	0	2.388	3.731	***
Q20	epu	0.016	0.02	0.8	0.423	-0.023	0.054	
Q20	Constant	4.256	0.825	5.16	0	2.636	5.876	***
Q30	gdp	0.997	0.314	3.18	0.002	0.381	1.613	***
Q30	gcf	0.241	0.078	3.1	0.002	0.089	0.394	***
Q30	lf	-1.301	0.301	-4.32	0	-1.893	-0.709	***
Q30	glb	-0.547	0.209	-2.62	0.009	-0.957	-0.138	***
Q30	pci	-1.215	0.263	-4.62	0	-1.731	-0.698	***
Q30	emission	3.568	0.217	16.42	0	3.142	3.995	***
Q30	epu	0.027	0.019	1.43	0.152	-0.01	0.063	
Q30	Constant	3.725	0.601	6.2	0	2.547	4.904	***
Q40	gdp	0.84	0.212	3.95	0	0.423	1.257	***
Q40	gcf	0.242	0.071	3.4	0.001	0.102	0.382	***
Q40	lf	-1.144	0.22	-5.21	0	-1.575	-0.713	***
Q40	glb	-0.523	0.221	-2.36	0.018	-0.957	-0.089	**
Q40	pci	-1.061	0.191	-5.56	0	-1.435	-0.686	***
Q40	emission	3.337	0.339	9.86	0	2.673	4.002	***
Q40	epu	0.015	0.027	0.56	0.579	-0.039	0.069	
Q40	Constant	3.921	0.702	5.58	0	2.543	5.299	***
Q50	gdp	0.782	0.31	2.53	0.012	0.174	1.39	**
Q50	gcf	0.19	0.078	2.42	0.016	0.036	0.344	**
Q50	lf	-1.036	0.297	-3.49	0.001	-1.619	-0.454	***
Q50	glb	-0.526	0.253	-2.08	0.037	-1.022	-0.031	**
Q50	pci	-0.966	0.266	-3.63	0	-1.488	-0.444	***

Q50	emission	2.799	0.318	8.81	0	2.175	3.422	***
Q50	epu	0.012	0.026	0.48	0.63	-0.038	0.063	
Q50	Constant	4.303	0.977	4.4	0	2.385	6.221	***
Q60	gdp	0.328	0.336	0.98	0.329	-0.332	0.988	
Q60	gcf	0.132	0.084	1.57	0.117	-0.033	0.298	
Q60	lf	-0.554	0.28	-1.97	0.049	-1.104	-0.003	**
Q60	glb	-0.674	0.278	-2.42	0.016	-1.22	-0.127	**
Q60	pci	-0.512	0.248	-2.06	0.039	-0.999	-0.025	**
Q60	emission	2.825	0.353	8.01	0	2.133	3.518	***
Q60	epu	0.052	0.034	1.56	0.12	-0.014	0.118	
Q60	Constant	5.807	0.978	5.94	0	3.886	7.727	***
Q70	gdp	-0.068	0.392	-0.17	0.863	-0.838	0.702	
Q70	gcf	0.289	0.072	4.02	0	0.148	0.43	***
Q70	lf	-0.353	0.347	-1.02	0.309	-1.035	0.328	
Q70	glb	-0.548	0.177	-3.1	0.002	-0.895	-0.201	***
Q70	pci	-0.373	0.328	-1.14	0.255	-1.017	0.27	
Q70	emission	2.501	0.609	4.11	0	1.305	3.697	***
Q70	epu	0.059	0.03	1.95	0.052	0	0.118	*
Q70	Constant	6.939	0.762	9.11	0	5.444	8.434	***
Q80	gdp	-1.482	0.355	-4.17	0	-2.18	-0.785	***
Q80	gcf	0.55	0.13	4.24	0	0.295	0.805	***
Q80	lf	0.702	0.231	3.04	0.002	0.249	1.156	***
Q80	glb	-0.595	0.209	-2.85	0.005	-1.006	-0.185	***
Q80	pci	0.668	0.236	2.83	0.005	0.205	1.131	***
Q80	emission	1.097	0.818	1.34	0.18	-0.509	2.703	
Q80	epu	0.1	0.028	3.6	0	0.045	0.154	***
Q80	Constant	10.055	1.241	8.1	0	7.619	12.491	***
Q90	gdp	-1.793	0.105	-17.04	0	-2	-1.587	***
Q90	gcf	0.712	0.047	15.19	0	0.62	0.804	***
Q90	lf	0.812	0.096	8.46	0	0.623	1	***
Q90	glb	-1.138	0.151	-7.52	0	-1.435	-0.841	***
Q90	pci	0.811	0.089	9.09	0	0.635	0.986	***
Q90	emission	-1.201	0.311	-3.86	0	-1.812	-0.59	***
Q90	epu	0.135	0.031	4.41	0	0.075	0.195	***
Q90	Constant	13.398	0.708	18.93	0	12.009	14.788	***

Sources: Authors estimates from secondary data of Statistical Review of World Energy dataset of British Petroleum (1995-2023) and World Development Indicators (1995-2023) of World Bank.

A2: Levin-Lin-Chu and Im-Pesaran-Shin Unit Root Test

Levin–Lin–Chu unit-root test	ED	GDP	GCF	LF	GLB	PCI	Emission	EPU
Unadjusted t	-0.8183	-4.2588	-5.1638	-4.4049	-14.8278	-3.7089	-2.3042	-9.1331
Adjusted t*	3.9791	-3.3602	-2.6722	-2.6332	-11.3613	-2.426	2.1448	-3.1484
p-value	1	0.0004	0.0038	0.0042	0	0.0076	0.984	0.0008
Im–Pesaran–Shin unit-root test								
t-bar	-0.1786	-1.4369	-1.145	-1.5203	-3.3231	-1.4148	-0.8099	-2.0354
t-tilde-bar	-0.2216	-1.349	-1.1026	-1.101	-2.6475	-1.308	-0.8009	-1.8556
Z-t-tilde-bar	7.8616	0.562	2.1573	2.1677	-7.8454	0.8277	4.1109	-2.7179
p-value	1	0.7129	0.9845	0.9849	0	0.7961	1	0.0033
Levin–Lin–Chu unit-root test for Difference								
Unadjusted t	-15.409	-15.735	-17.915	-12.1546	-15.6676	-15.676	-19.3714	-23.2999
Adjusted t*	-7.7852	-9.1142	-10.725	-6.2461	-8.4953	-8.9927	-9.6758	-13.487
p-value	0	0	0	0	0	0	0	0
Im–Pesaran–Shin unit-root test for Difference								
t-bar	-4.6118	-3.76	-4.4005	-3.4987	-4.2996	-3.6552	-5.3355	-5.7165
t-tilde-bar	-3.3383	-2.967	-3.2723	-2.8011	-3.2096	-2.9156	-3.5874	-3.7717
Z-t-tilde-bar	-12.367	-9.9571	-11.939	-8.8804	-11.5317	-9.6239	-13.9831	-15.1793
p-value	0	0	0	0	0	0	0	0
Fixed-N exact critical values								
1%	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82
5%	-1.73	-1.73	-1.73	-1.73	-1.73	-1.73	-1.73	-1.73
10%	-1.69	-1.69	-1.69	-1.69	-1.69	-1.69	-1.69	-1.69

Sources: Authors estimates from secondary data of Statistical Review of World Energy dataset of British Petroleum (1995-2023) and World Development Indicators (1995-2023) of World Bank.
Note: (Im et al., 2003; Levin, Lin, & James Chu, 2002) Unit Root Test and Unit Root Test for Difference performed.

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