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Research Article

Do Environmental Policy Stringency and Financial Development Promote a Sustainable Energy Future in the United States? Evidence from Quantile-on-Quantile Regression

Babatunde Sunday Eweade
Department of Economics, Faculty of Business and Economics, Eastern Mediterranean University Northern Cyprus, Mersin, Turkey

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ABSTRACT

Over the past few years, environmental challenges and the impacts of climate change have gained significant attention among policymakers and energy experts. Conforming to the objectives outlined in Sustainable Development Goals 7 and 13, which underscore the importance of clean energy provision and climate change mitigation, this study aligns with the sustainability targets set forth in Vision 2030. The research explores the intricate relationships among financial development, the stringency of environmental policies, advancements in information and communication technology (ICT), human capital, and economic growth. It aims to understand their combined effects on sustainable energy in the United States from the initial quarter of 1990 to the concluding quarter of 2020. Employing quantile-based methods including multivariable quantile-on-quantile regression (MQQR) and non-parametric quantile causality, our research reveals a positive influence across all quantiles for financial development, economic growth, environmental policy stringency, ICT innovations, and human capital on sustainable energy. Additionally, our quantile causality analysis confirms these factors significantly predict sustainable energy in the United States. These findings form the basis for policy recommendations.

1. INTRODUCTION

Promoting sustainable energy, particularly renewable energy sources, is crucial in addressing global issues such as climate change, ecological degradation, and energy security. The shift towards renewable energy can substantially lessen carbon (CO_2) emissions, thereby mitigating the negative effects of climate change [1]. According to [2], renewable energy sources accounted for almost 30% of global electricity production in 2022, avoiding around 2.6 billion tons of CO_2. Renewable energy also enhances energy access and security by enabling communities to become self-sufficient and reducing dependence on fossil fuel imports [3]. The Paris Agreement, adopted in 2015, highlights the importance of renewable energy in reducing global warming to below 2^0C. Countries have pledged to reduce greenhouse gas emissions (GHGE) through nationally determined contributions (NDCs), with renewable energy playing a vital role [4]. SDG 13 specifically addresses climate action and resilience to climate-related hazards. By investing in renewable energy technologies and supporting policies, it is not far to achieve a greener, more resilient,

*Corresponding author. Email: babatunde.sunday.eweade@emu.edu.tr

and sustainable future, aligning with the objectives of the Paris Agreement, COP conferences, and SDGs 7 and 13.

[5] outline a significant upswing in the incorporation of renewable energy within the United States (US), marking a substantial shift in the nation's overall energy consumption patterns. Despite a continuous increase in the country's total energy consumption due to population growth and economic expansion, the proportion of renewable energy has been steadily increasing [6, 7]. Renewable energy sources have made considerable progress due to supportive policies, declining technology costs, and public demand. The growth of clean energy in the US can be attributed to several factors, including federal and state-level policies such as clean energy standards and production tax credits, which have incentivized the deployment of renewable energy projects and facilitated market growth [8]. As the US population continues to grow, energy consumption and its demand naturally increase; however, sustainable energy development aims to decouple this growth from CO_2 emissions [9, 10]. Furthermore, as the economy expands due to economic growth, there is a greater need for electricity and power generation. By promoting sustainable energy, the US can ensure that economic growth is coupled with a clean energy transition. At recent, sustainable energy sources contributed 12.1% of total primary energy consumption in the US in 2020, a significant increase compared to previous years [2]. The surge in renewable energy is particularly noteworthy within the electricity sector, where it accounted for 21.2% of total electricity generation in 2020, as reported by the International Energy Agency [2].

The role of economic growth (GDP) in sustainable energy is multifaceted, encompassing both positive and negative aspects [11, 12]. On the one hand, GDP drives increased energy demand, potentially leading to a higher reliance on fossil fuels [13]. However, it also creates opportunities for investment in and deployment of clean energy technologies. For example, a study by [14] found that GDP positively affects clean energy, indicating that as economies expand, there is a tendency to invest more in renewable energy sources. This observation is further supported by [12], who discovered that nations with higher GDP per capita are incline to have a greater share of sustainable energy in their energy mix. These arguments suggest that economic growth can facilitate the transition to sustainable energy by providing the necessary financial resources and technological advancements. However, it is crucial to ensure that economic growth is decoupled from unsustainable energy consumption patterns, such as overreliance on fossil fuels that increase the greenhouse gas emissions and harm the environmental quality [15]. Similarly, effective environmental policy (EPS) provides the necessary incentives and regulations to promote the acceptance of green energy sources and encourage energy efficiency [16]. These policies often include initiatives such as clean energy standards, feed-in tariffs, carbon pricing mechanisms, and subsidies for clean technologies. A study by [17] supports the notion that EPS positively affects renewable energy consumption, leading to increased deployment of renewable energy technologies. Similarly, [18] emphasizes the significance of a robust regulatory framework and supportive policies in driving sustainable energy consumption and reducing CO_2 emissions. Poorly implemented or inconsistent policies can hinder progress and discourage investments; however, well-designed and consistent environmental policies are important in providing market signals, reducing investment risks, and fostering technological innovation within the renewable energy sector [19].

Financial development (FD) is vital in facilitating sustainable energy usage. Adequate FD provides the necessary capital, investment opportunities, and financial instruments to support the development renewable energy technologies [20]. Moreover, financial institutions can contribute to increasing adoption and capacity expansion of renewable energy by providing increases investments [21]. These arguments suggest that FD incentivizes renewable energy projects by providing access to capital, reducing financing costs, and fostering technological innovation. However, it is essential to ensure that FD aligns with sustainable practices and does not solely focus on conventional energy investments. Human capital (HC) is critical for the progress, implementation, and operation of clean energy technologies and practices.

Investing in HC development, such as providing specialized training and fostering research and innovation accelerate the transition to sustainable energy [21]. However, challenges may arise in terms of the availability and distribution of HC, as certain regions or communities may lack the necessary skills and resources, and may adversely affect the energy transition that are crucial to address by implementing inclusive policies that ensure equal access to education, training, and opportunities in the sustainable energy sector [22]. ICT play a crucial role in shaping sustainable energy consumption. The integration of ICT solutions in the energy sector has the potential to enhance energy efficiency, optimize energy management, and encourage the integration of sustainable energy sources [23]. Adopting smart grid technologies, advanced metering systems, and energy management platforms positively contribute to energy savings and a more sustainable energy system, demonstrating the significance of ICTI for sustainable energy [24]. Moreover, [25] empirically proved the significant role of ICTI in enabling demand response programs, promoting energy conservation, and supporting the integration of distributed energy resources. Furthermore, ICTI empower consumers, enhance energy system flexibility, and enable real-time monitoring and control of energy consumption [16]. While previous studies have explored the relationship between individual factors and sustainable energy, this study uniquely combines these factors into a comprehensive framework, providing a holistic understanding of their collective influence on sustainable energy consumption. Secondly, this study employs advanced and robust econometric approaches not used in previous research, such as Multivariate Quantile-On-Quantile Regression, Nonparametric Quantile Causality, and Recursive Cross-Quantilogram analysis.

These techniques allow for examining heterogeneous effects across different quantiles, capturing potential nonlinear relationships and offering valuable insights into the dynamics between the variables. For example, Multivariate Quantile-On-Quantile Regression allows for a thorough examination of the conditional distributional dependencies, enabling a more comprehensive understanding of the relationships among the variables. Similarly, Nonparametric Quantile Causality analysis provides insights into the causal linkages and directionality of the relationships, allowing for a more exhaustive understanding of how changes in the independent variables influence sustainable energy consumption at different quantiles. The findings of this study are instrumental in guiding policymakers in designing effective strategies and policies to promote sustainable energy in the US. By identifying the significant factors that contribute to sustainable energy consumption and understanding their causal dynamics, policymakers can develop targeted interventions and incentives to accelerate the transition towards sustainable energy. Furthermore, these findings provide valuable insights into how the US can align its policies with the SDGs goals 7 and 13 by leveraging the positive aspects of economic growth, financial development, ICT innovations, environmental policy, and human capital to drive the sustainable energy transition, reduce carbon emissions, and foster a cleaner and more resilient energy future.

2. LITERATURE REVIEW

The energy security concerns that have arisen in the wake of the Russia-Ukraine war have compelled several nations to reassess their reliance on traditional energy sources. In response, many countries are transitioning towards sustainable energy to meet their increasing energy demands. The recent COP27 conference in Egypt emphasized the crucial need to elevate the percentage of sustainable energy within the total energy mix to attain carbon neutrality targets. Taking assertive steps to combat climate issues, the United States, ranking as the second-largest global emitter of CO_2, is actively engaged in addressing environmental challenges. The above highlights have generated the need to look at economic factors driving sustainable energy around the world based on past studies documented in energy and environmental literature. For instance, [26] investigated how to formulate policies regarding green energy growth in top 10 clean energy-consuming nations applied the third generations tests from 1990 to 2017 to evaluate drivers of sustainable energy. The study results show that ICT innovations improve sustainable energy while economic policy uncertainty decreases it. In addition, HC and FD enhance sustainable energy in the long-term. In the same vein, the study of [27] using Sub-Saharan African economies as a case highlighted the role of economic growth and financial development in bolstering sustainable energy growth in the selected nations. Moreover, [28] used China from 2011–2020 to inspect the drivers of green energy utilizing recent panel techniques and the study result highlights the sustainable energy bolstering role of green finance and private sector participation. Furthermore, [22] employed the G-7 countries from 1995 to 2017 to explore the sustainable energy drivers in G7 nations. The study relied on second generation techniques and the study discoveries show that R&D, innovation and human capital are the main driver of sustainable energy in the G7 nations while non-renewable energy lessen the growth of sustainable energy. Likewise, using the data from 1980-2017, the study of [29] on the green energy drivers in Turkey using the ARDL approach documented the sustainable energy increasing role of human capital stock and economic growth. Likewise, using the OECD economies, and data from the period 1965–2014, [30] used the panel techniques to evaluate the drivers of sustainable energy and the results show that real growth and human capital are the main cause of sustainable energy growth in the selected nations. Moreover, [31] investigation using the VECM on the sustainable energy determinants in Turkey from 1980 to 2019 reported that financial development is Turkey's main architect of sustainable energy growth. [21] study on the role of innovation and FD in promoting sustainable energy using data from 2000 to 2014 reported the sustainable energy increasing role of financial development, economic growth and innovations. [19] explored the role of EPS in bolstering sustainable energy using data from 1990 to 2016 and the study research highlighted the sustainable energy increasing role EPS. [22] to formulate policies that will bolster clean energy consumption in the OECD nations employed the CS-ARDLL in their study on drivers of sustainable energy from 1990 to 2018. The authors highlight financial development, environmental policy stringency, and human capital energy prices as the main drivers of sustainable energy. [18] study in Slovakia, Hungary, and Czech Republic on the drivers of sustainable energy using data from 1993–2012 after controlling for real growth reported that environmental policy stringency bolsters sustainable energy in the selected nations.

2.1 LITERATURE GAP

The summary of the aforementioned studies allows us to emphasize the following points: Firstly, research on the determinants of sustainable energy has been conducted for individual countries (such as Turkey, United States, Brazil, France, China, among others) as well as groups of nations (such as OECD nations, BRICS, G7 nations, EU nations, and others). Secondly, the majority of techniques employed are time-domain methods, including autoregressive distributed lag (ARDL), Granger causality, fully modified OLS (FMOLS), Toda Yamamoto causality, Panel OLS (POLS), vector error correction model (VECM), dynamic ARDL (DARDL), and others. Thirdly, none of the studies consider the role of other variables in the relationship between the dependent and independent series. Instead, they assume that only a single independent variable can influence sustainable energy. These points highlight a gap in the existing literature, calling for further analysis and investigation. This study addresses the gaps in previous research in the following ways: Firstly, we explore the impact of financial development, environmental policy stringency, human capital, ICT innovations, and economic growth on sustainable energy by considering the tails of both the regressor and dependent indicators.

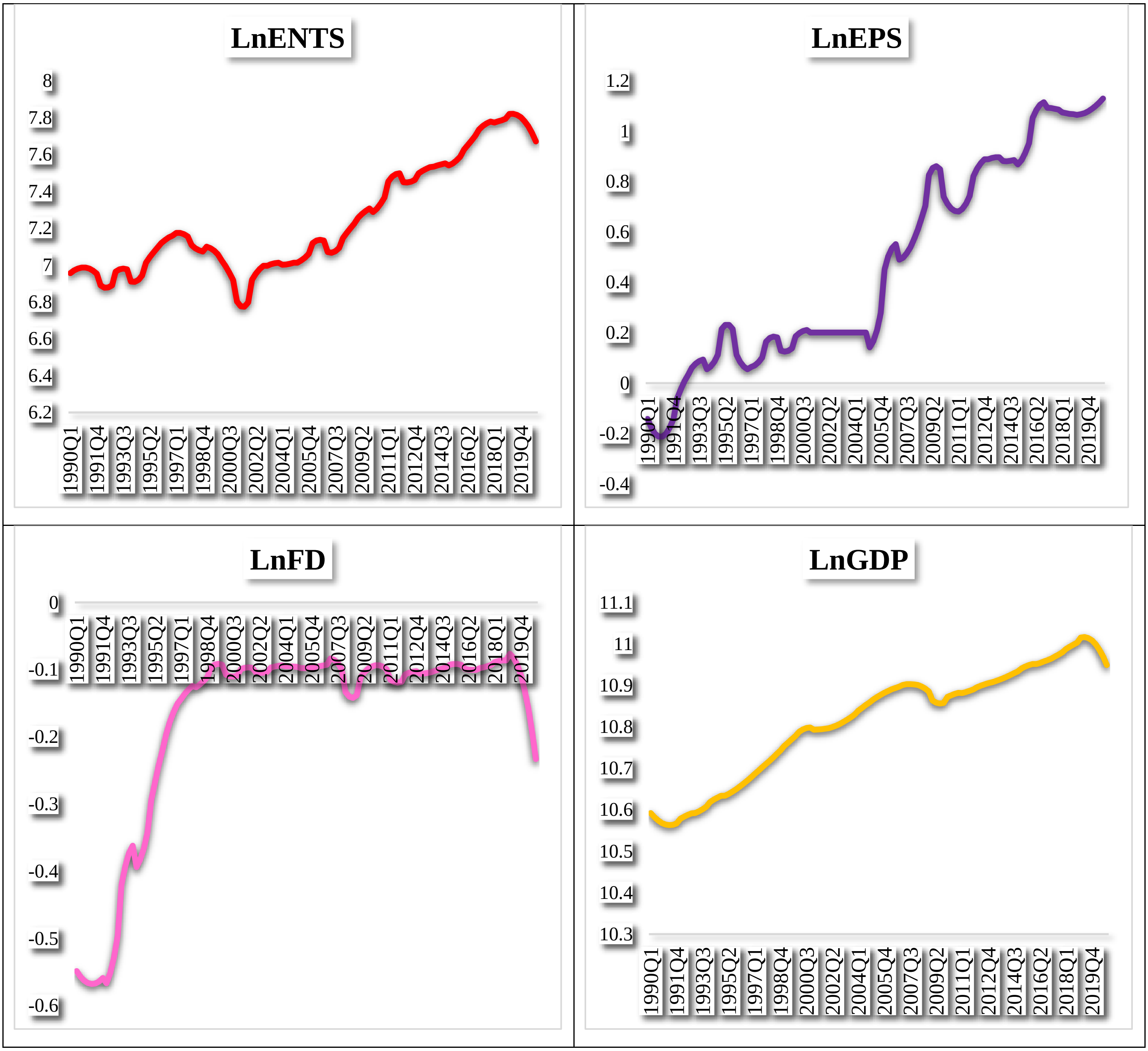
3. DATA AND METHODOLOGY

3.1. Data

This empirical study investigates the impact of financial development, environmental policy stringency, human capital, and economic growth on sustainable energy in the United States. The analysis utilizes data spanning from 1990 to 2020. The United States is chosen as the focal point of this research for several reasons. Firstly, the United States represents a substantial portion of the world's net wealth. Secondly, it is recognized as a primary energy consumer and a frontrunner in developing clean energy technologies. Thirdly, the United States ranks as the second-largest emitter of CO_2 globally, accounting for approximately 14.02% of total emissions in 2020 [33]. Given its high-income level, significant contribution to global CO_2, and prominent position in energy consumption and clean energy initiatives, it is crucial to examine the factors driving sustainable energy in the United States. The study focuses on sustainable energy as the dependent variable, while FD, EPS, GDP and HC serve as explanatory variables. Table 1 reveals the data source and Figure 1 depicts the trend of the variables under inspection respectively.

Table 1: Data Source and Measurement

Variables	Sign	Measurement	Source
Environmental Policy Stringency	EPS	Index	OECD (2023)
Sustainable Energy	ENT	Share of primary energy from renewables	BP (2023)
Economic Growth	GDP	GDP Per Capita 2015US$	WB (2023)
Human Capital	HC	Index	UN (2023)
Environmental related ICT innovations	EICTI	Patents in environmental related ICT	OECD (2023)
Financial Development	FD	Index	IMF (2023)


LnENTS
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
1990Q1
1991Q4
1993Q3
1995Q2
1997Q1
1998Q4
2000Q3
2002Q2
2004Q1
2005Q4
2007Q3
2009Q2
2011Q1
2012Q4
2014Q3
2016Q2
2018Q1
2019Q4
LnEPS
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1990Q1
1991Q4
1993Q3
1995Q2
1997Q1
1998Q4
2000Q3
2002Q2
2004Q1
2005Q4
2007Q3
2009Q2
2011Q1
2012Q4
2014Q3
2016Q2
2018Q1
2019Q4
LnFD
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
1990Q1
1991Q4
1993Q3
1995Q2
1997Q1
1998Q4
2000Q3
2002Q2
2004Q1
2005Q4
2007Q3
2009Q2
2011Q1
2012Q4
2014Q3
2016Q2
2018Q1
2019Q4
LnGDP
11.1
11
10.9
10.8
10.7
10.6
10.5
10.4
10.3
1990Q1
1991Q4
1993Q3
1995Q2
1997Q1
1998Q4
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2016Q2
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2019Q4

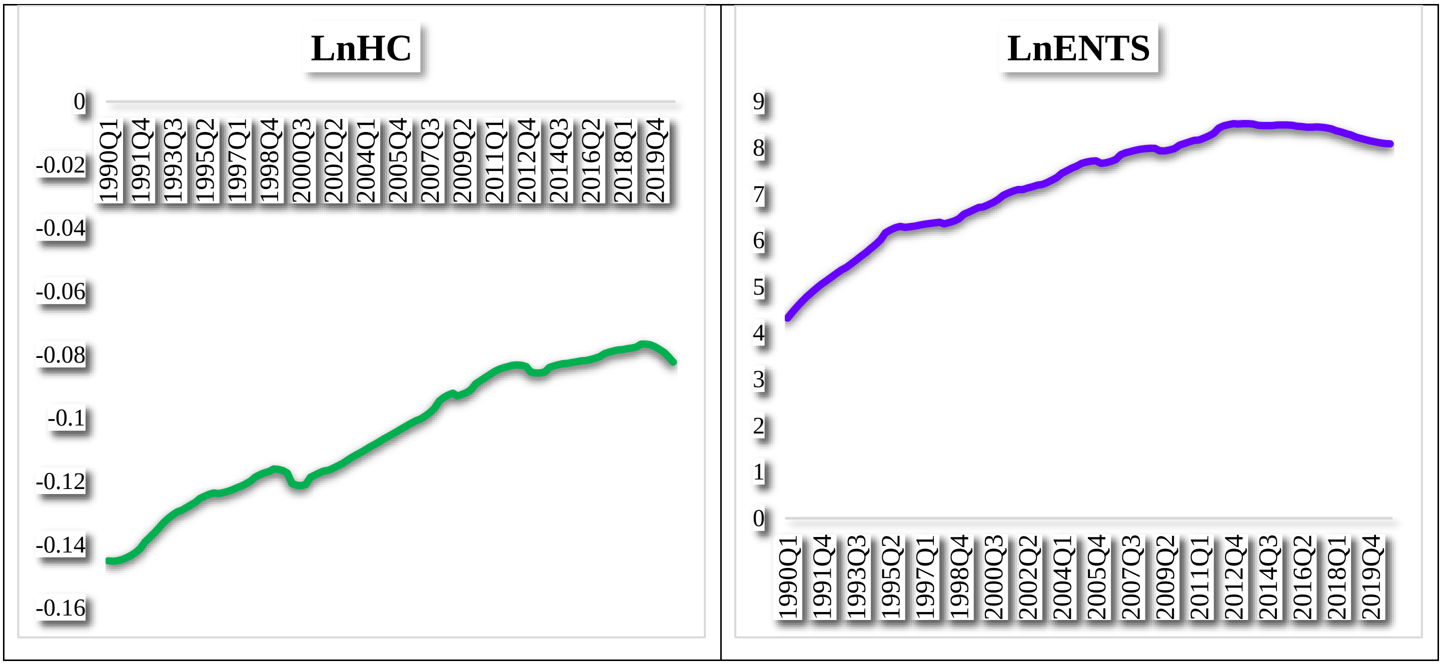


Figure 2: Log form of the variables from from 1990/Q1 to 2020/Q4.

3.2 Empirical Methods

In this investigation, we propose that the application of the nonparametric method using QQR regression, as pioneered by [34], may introduce an empirical challenge related to omit variable bias, primarily due to its reliance on the bivariate case. To mitigate this potential issue, we employ a recently developed technique called MQQR, presenting a nonparametric modeling approach. This model provides a framework for evaluating the influence of FD, EPS, HC, and GDP on sustainable energy in the United States. To commence, we establish the functional relationships among these variables as follows:

$$\mathrm{LnENT_t} = \mathrm{f}(Ln\mathrm{FD_t}, \mathrm{LnEPS_t}, \mathrm{LnGDP_t}, \mathrm{LnHC_t}, \mathrm{LnEICTI_t}) \quad (1)$$

Wherein f represents a function, EPS, HC, EICTI, GDP, FD and ENT portray environmental policy stringency, human capital, environmental ICT innovations, economic growth, and financial development. The econometric model representing the interrelationship established in Equation 1 can be illustrated as follows:

$$\mathrm{LnENT_t} = \beta_0 + \beta_1\mathrm{LnFD_t} + \beta_2\mathrm{LnEPS_t} + \beta_3\mathrm{LnGDP_t} + \beta_4\mathrm{LnHC_t} + \beta_5\mathrm{LnEICTI_t} + \varepsilon_t \quad (2)$$

Wherein the constant is shown by β_0, time is shown by while ε_t is the error term.

In this phase, we also conduct the conventional QQR method to facilitate a comparative analysis. Inspired by [34], we investigate the dynamic interplay between two variables across different segments of their distributions, we opt for a nonparametric approach called quantile-on-quantile (QQR). In this analysis, we designate x as the independent variable and y as the dependent variable. The QQR approach, outlining the examination of the interrelationship between the quantiles of x and y, is depicted as follows:

$$\underbrace{y_t = \beta_0(\theta,\Phi) + \beta_1(\theta,\Phi)\,(x_t - x^{\Phi}) + \propto^{\theta} y_{t-1} + \varepsilon_t^{\theta}}_{*} \quad (3)$$

Here, θ and Φ represent quantiles ranging from 0.05 to 0.95 for the independent and dependent indicators. The term ε_t^{θ} illustrates the residual term, assumed to have a zero θ-quantile. Additionally, the interrelationship between x and y as a whole is identified by part (*) of Equation 2, representing the dependence between their distributions.

To accomplish this, we consider $x_1, x_2 \ldots x_n$ as the explanatory variables and y as the regressand variable, our multivariate quantile-on-quantile (QQR) model, designed to scrutinize the interrelationship between y and x across different quantiles (0.05-0.95), is delineated as follows:

$$y_t = \beta_0(\theta,\Phi_1,\Phi_2 \ldots \Phi_n) + \beta_1(\theta,\Phi_1)(x_{1t} - x_1^{\Phi_1}) + \beta_2(\theta,\Phi_2)(x_{2t} - x_2^{\Phi_2}) + \beta_n(\theta,\Phi_n)(x_{nt} - x_n^{\Phi_n}) + \propto^{\theta} y_{t-1} + \epsilon_t^{\theta} \quad (4)$$

In this equation, $\Phi_1, \Phi_2 \ldots . \Phi_n$ illustrate the quantiles of $x_1, x_2 \ldots x_n$, while θ portrays the y quantile. The slope coefficients of the dependent variable and independent variables quantiles are portrayed by $\beta_1, \beta_2 \ldots . \beta_n$. In line with the approach proposed by [34], we set the bandwidth size to 0.05 as the QQR approach requires an optimal determination of the bandwidth. Fig. 1 provides a visual illustration of the analysis flowchart.

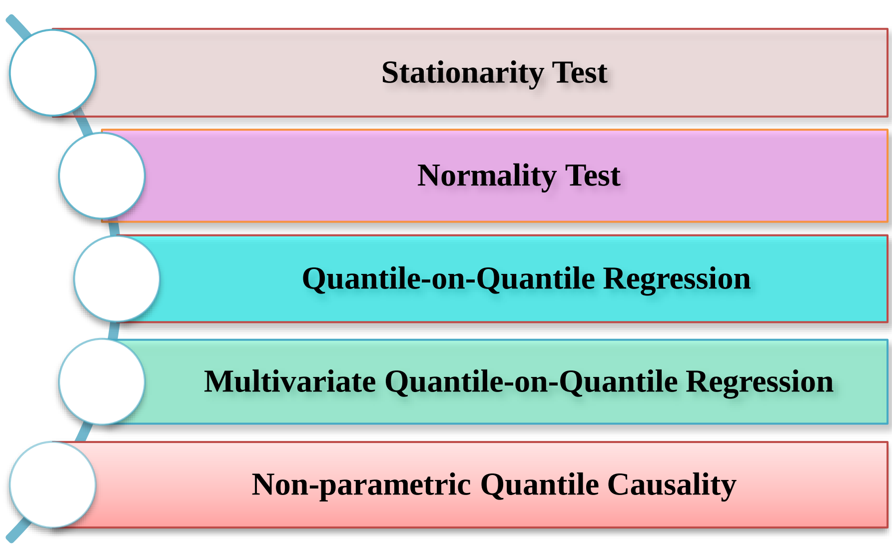


Figure 1: Flow of the study

4. RESULTS AND DISCUSSIONS

4.1. Preliminary Estimation

This study seeks to assess how FD, HC, EPS, GDP, and EICTI collectively impact sustainable energy in the United States. Before conducting the main analysis, we first explore the features of the series, as obtainable in Table 1. According to the standard deviation findings, economic growth exhibits lower volatility, whereas environmental ICT innovation demonstrates high volatility. It is also worth noting that sustainable energy and environmental policy stringency are positively skewed (i.e., majority of the observations are concentrated in the distribution's left tail) while financial development, human capital, economic growth and environmental ICT innovation are negatively skewed (i.e., majority of the observations are concentrated in the distribution's right tail). The kurtosis values of all the series, except for financial development, are less than 3, indicating that their distributions are platykurtic (i.e., a distribution with narrow tails compared to a normal distribution).

Table 2: Descriptive Statistics

	LnENTS	LnEPS	LnFD	LnGDP	LnHC	LnEICTI
Mean	7.2365	0.4696	-0.1734	2.3809	-0.1050	7.2569
Median	7.1254	0.2314	-0.1043	2.3849	-0.1053	7.6724
Maximum	7.8205	1.1293	-0.0763	2.3994	-0.0766	8.5236
Minimum	6.7739	-0.2121	-0.5677	2.3573	-0.1452	4.3237
Std. Dev.	0.3014	0.4141	0.1451	0.0124	0.0208	1.1585
Skewness	0.5928	0.2024	-1.8659	-0.5259	-0.2295	-0.7686
Kurtosis	2.0154	1.6099	5.0003	2.0482	1.7900	2.5065
Jarque-Bera	12.2716	10.830	92.628	10.398	8.6531	13.468
Probability	0.0021	0.0044	0.0000	0.0055	0.0132	0.0011
ΔADF	-3.6059**	-5.0951***	-6.8038***	-3.6953**	-5.6494***	-6.0011***
ΔPP	-5.2946***	-5.6014***	-4.8288***	-3.2950**	-4.7858***	-5.1725***
Note: ***P<1% and **P<5%						

4.2. Nonlinearity Test Results

Exploring the nonlinearity of the series is crucial to determine the most suitable methodology for analysis. In this study, the BDS test initiated by [35] for non-linearity is employed to enhance the methodological aspect of the existing literature, ensuring accurate estimation (refer to Table 3). The results of the BDS test strongly confirm the presence of nonlinearity in the interrelationship between the variables, as evidenced by the dismissal of the null hypothesis across all dimensions. These findings indicate the inadequacy of a linear predictive regression model and emphasize the need for a nonlinear approach. Building on this understanding, the current study adopts quantile-based techniques, which are nonlinear methods, to effectively analyze the data.

Table 3: BDS Test Results

	LnENTS	LnEPS	LnFD	LnGDP	LnHC	LnICTI
M2	38.802***	38.802***	16.444***	39.258***	54.698***	38.015***
M3	40.785***	40.785***	17.428***	41.953***	58.149***	40.703***
M4	43.553***	43.553***	18.611***	45.363***	62.599***	43.997***
M5	47.828***	47.828***	20.337***	50.289***	69.241***	48.731***
M6	53.936***	53.935***	22.691***	57.037***	78.453***	55.188***
Note: ***P<1%						

4.3. Cointegration Results

The recognition of the nonlinear characteristics of the variables led us to employ a nonlinear cointegration method known as quantile cointegration, as suggested by [36]. The outcome of the quantile cointegration analysis, as presented in Table 4, provide strong evidence of cointegration between sustainable energy and the regressors across various quantiles. This indicates a persistent long-term association among these variables implying that shifts in the regressors have a long-term influence on sustainable energy levels. The quantile cointegration results portray the need of taking nonlinear dynamics into account when analyzing the interaction between these indicators.

Table 5. Quantile Cointegration

Models	Coefficient	$Sup_{\tau}\|V_{\pi}(\tau)\|$	CV-1%	CV-5%	CV-10%
$LnENT_t$ Vs $LnEPS_t$	β	8303	6182	4283	2037
	γ	927	680	455	274
$LnENT_t$ Vs $LnFD_t$	β	3702	2856	1172	793
	γ	283	152	106	63
$LnENT_t$ Vs $LnGDP_t$	β	4938	3027	1936	1042
	γ	376	259	149	117
$LnENT_t$ Vs $LnHC_t$	β	7721	5628	3895	1726
	γ	503	372	264	146
$LnENT_t$ Vs $LnICTI_t$	β	58I3	4673	2749	1037
	γ	394	223	136	85

Note: By using a grid of 19 quantiles (0.05–0.95) that are evenly spaced apart, the t-statistic for quantile cointegration is achieved. Supremum norm estimations of the parameters (β and γ) are also provided, whilst CV10, CV5, and CV1 correspondingly denote their critical values at the 10%, 5% and 1% levels of significance.

4.4. Traditional and Multivariate Quantile-On-Quantile Regression

In this investigation, we employ the multivariate Quantile Regression (QQR) technique to analyze the effects of financial development, environmental policy stringency, human capital, and economic growth on sustainable energy. To facilitate comparison, we also employ the conventional QQR approach. Figure 3 showcases the slope coefficients estimated by both the multivariate and traditional QQR approaches. The right and left plots portray the multivariate QQR and traditional QR estimates. The analysis reveals notable distinctions between the outcomes obtained from the two employed methods. Figure 3 visually presents these disparities, indicating that while the traditional and multivariate Quantile Regression (QQR) approaches exhibit some similarities, their results diverge significantly. This observation underscores the potential for misleading conclusions if the influence of other factors is not taken into account. In line with the findings of [37], who advocated for the use of multivariate nonparametric causality analysis, our study affirms that incorporating additional factors that may impact the relationship leads to more accurate outcomes in assessing the interrelationships. In conclusion, the empirical evidence presented in Figure 3 underscores the significance of considering the influence of other factors in order to evade ambiguous results. Disregarding the impact of these factors can result to inaccurate and probable misleading conclusions.

Figure 3 reveals a relationship between EPS and ENT across different quantiles. In the lower tails (0.1-0.35) of both EPS and ENT, there is a positive effect of EPS on ENT. On the other hand, in the higher tails

(0.70-0.95) of ENT, as well as across all quantiles of EPS, there is a positive effect of EPS on ENT. In summary, the results suggest that, in the majority of quantiles, sustainable energy in the USA is positively influenced by environmental policy stringency. Nevertheless, the association becomes negative at some quantiles, suggesting a more complicated dynamic. The outcomes of this investigation indicate that the implementation of stringent environmental policies in the USA shows a momentous character in driving the growth of sustainable energy. These policies effectively boost the utilization and adoption of sustainable energy sources, thereby contributing to a substantial lessening in ecological deterioration. The results align with the research directed by [18], which emphasizes that stringent environmental policies send a powerful and clear message to the investors and market regarding the obligation to shift towards greener and more clean energy solutions.

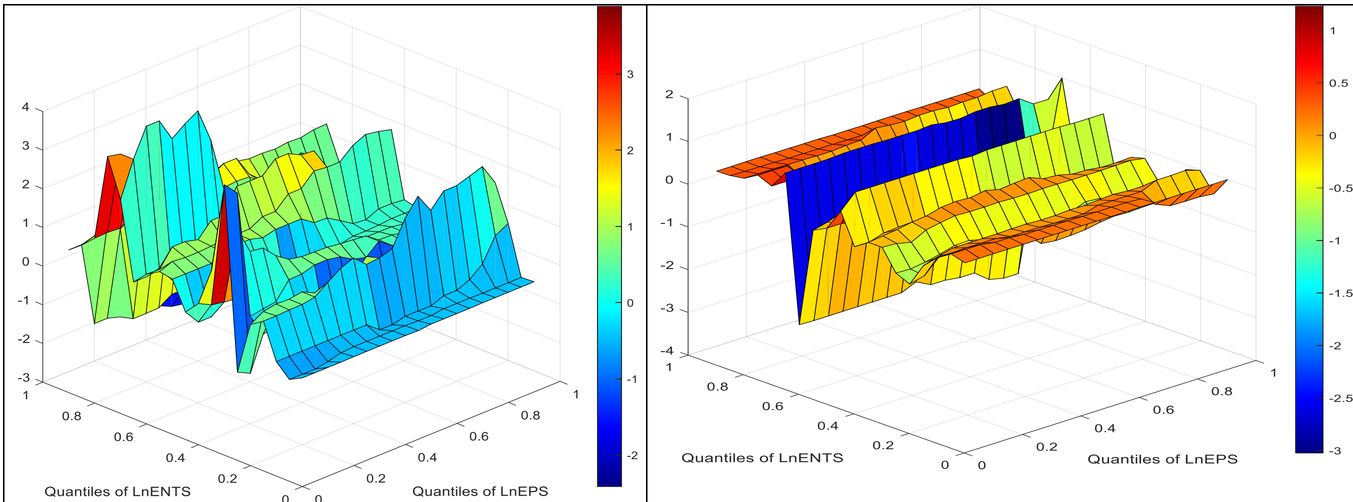
Additionally, the research by [38] highlights the benefits of stringent ecological policies, which include reduced regulatory uncertainty, long-term stability, and amplified investor confidence. These factors contribute to greater financial participation and support in renewable energy ventures. Similarly, the study by [19] concludes that ecological policy stringency plays a pivotal role in promoting research and development operations specifically aimed at advancing green energy technologies. Such policies serve as a catalyst for technological progress, facilitating breakthroughs in the areas of green energy storage, generation, and integration systems. These findings highlight the critical significance of strong environmental policies in establishing a climate conducive to renewable energy innovation and development. The research of [11] also found that implementing strong environmental policies encourages energy diversification, reduces reliance on fossil fuels, and improves energy security. [39] supported our findings by suggesting that rigorous environmental rules stimulate demand for sustainable energy while simultaneously designing cost reduction and incentives for technological advancement.

Figure 4 illustrates the impact of FD on sustainable energy (ENT) in the United States, taking into account the role of EPS, GDP, HC, and EICTI. Across the majority of quantiles, there is compelling evidence indicating a favorable outcome or positive influence of financial development on sustainable energy. This finding aligns with expectations, considering the maturity of the USA's financial system. The availability of diverse financial institutions and tools, facilitated by financial development, simplifies the process of securing funding for green energy projects. This funding plays a crucial role in supporting infrastructure deployment, technological advancements, and project development for clean energy enterprises and project developers. [40] further emphasize that FD can contribute to lessening capital costs associated with clean energy projects. These findings highlight the significant role of FD in facilitating the growth and financing of sustainable energy initiatives in the United States. Consequently, highly developed financial markets can provide numerous advantages, including lower transaction costs, increased liquidity, and competitive interest rates. These favorable financial conditions contribute to reducing the overall capital costs associated with clean energy initiatives, making them economically feasible. Similar findings have been reported by [41] in their respective studies, highlighting the role of financial development in facilitating innovative financing structures for clean energy sources. Moreover, our research findings align with the study conducted by [42], which emphasized the importance of financial development in enabling long-term project funding for green energy.

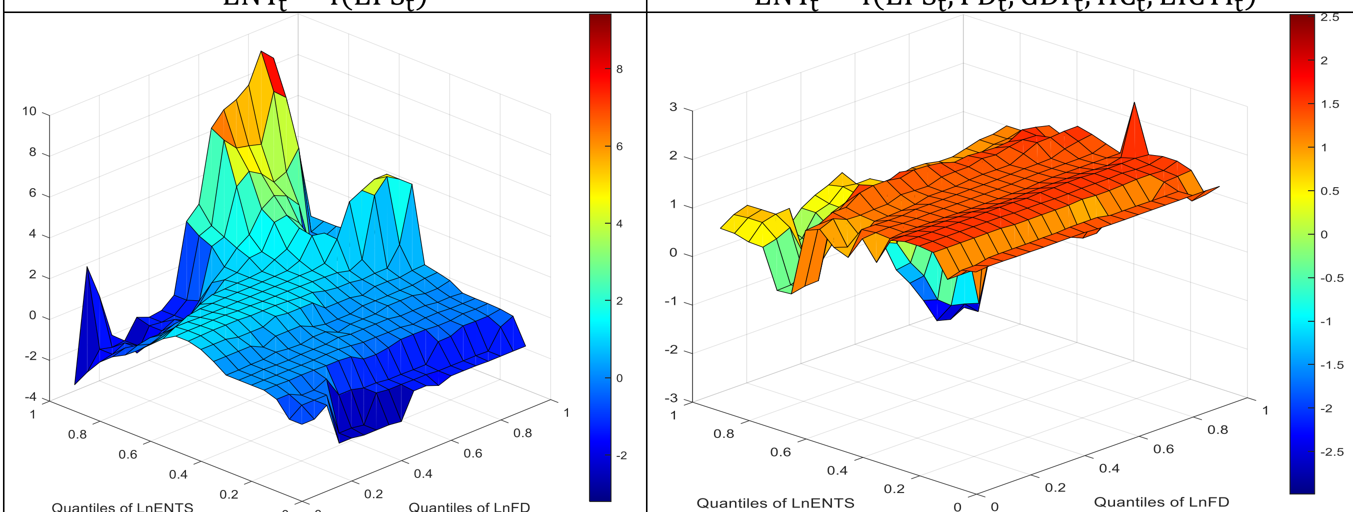
Figure 5 illustrates the impact of GDP on sustainable energy, taking into account the effects associated with the rigor of environmental policy measures, human capital, financial development, and environmental ICT innovations in the United States. In the lower quantiles of both sustainable energy and economic growth (0.1-0.35), economic growth shows a negative effect on sustainable energy. However, the effect becomes positive and statistically significant in the middle and higher quantiles (0.40-0.95) of both variables. This portrays that as economic expansion progresses and attains higher levels, it positively influences the utilization and development of sustainable energy sources in the United States. These findings come as no surprise, as economic growth typically leads to increased energy consumption due to expanding sectors and growing populations. This surge in energy demand creates an opportunity for renewable energy sources to fulfill a portion of the escalating energy needs. With economies expanding, there is an expansion acknowledgment of the importance of diversifying energy sources and reducing dependence on dirty fuels. Consequently, there is increased investment in renewable energy projects, infrastructure development, and technological advancements. As highlighted by [43], economic expansion can serve as a catalyst for innovation and technical enhancements within the realm of renewable energy.

Figure 6 illustrates the impact of human capital (HC) on sustainable energy (ENT) in the United States, taking into account the role of FD, EPS, GDP, and EICTI. Across all quantiles, there is strong evidence of a positive effect of human capital on sustainable energy. Thus, increase in human capital improves sustainable energy. This result is expected as developed human capital plays a significant role in facilitating the transition of economies towards more sustainable energy sources, particularly clean energy. Moreover, human capital has the potential to drive technological advancements, leading to increased adoption of green energy solutions. Therefore, a well-educated workforce is essential in facilitating the shift towards clean energy sources. Skilled professionals play a vital role in driving innovation and development in clean energy systems, creating more cost-effective and efficient solutions [44]. Professionals with specialized expertise can share their experiences, best practices, and technical know-how with others in the industry, thereby promoting capacity building and skill development. This transfer of information improves understanding and implementation of clean energy technologies, facilitating their adoption and integration into existing energy systems.

Figure 3: Effect of Environmental Policy Stringency on Energy Transition

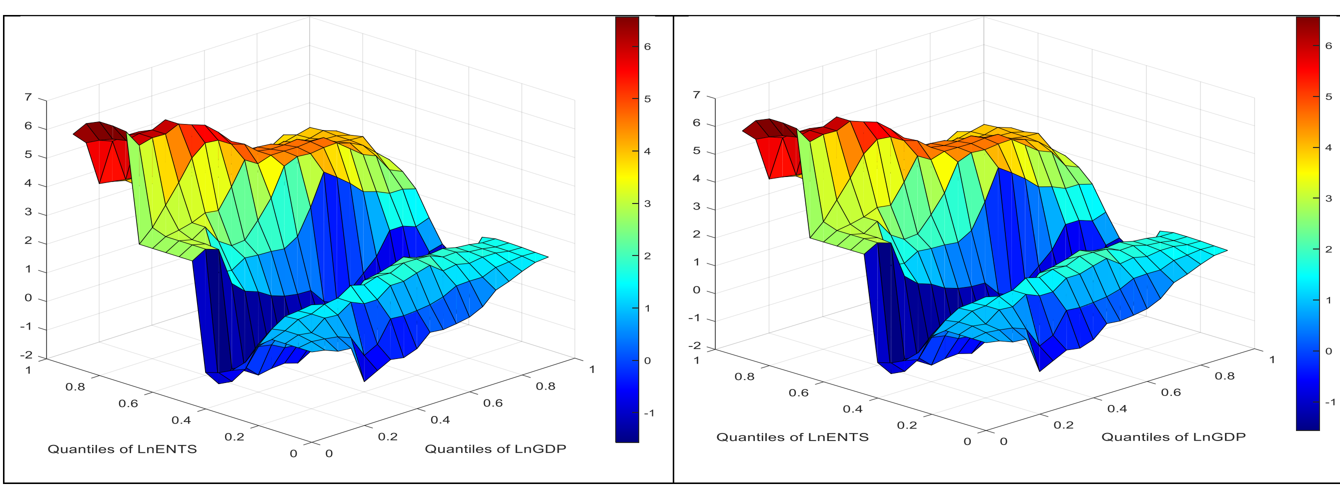


Traditional QQR	**Multivariate QQR**
$\mathrm{ENT_t} = \mathrm{f(EPS_t)}$	$\mathrm{ENT_t} = \mathrm{f(EPS_t, FD_t, GDP_t, HC_t, EICTI_t)}$



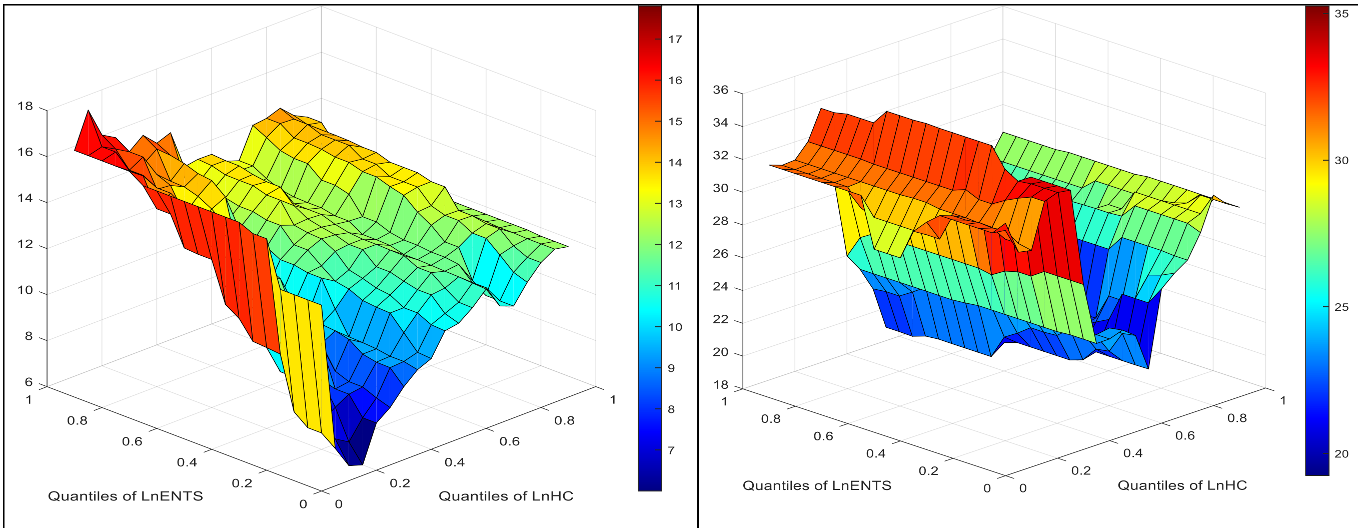
$\mathrm{ENT_t} = \mathrm{f}(FD_t)$	$\mathrm{ENT_t} = \mathrm{f}(FD_t, EPS_t, \mathrm{GDP_t}, \mathrm{HC_t}, \mathrm{EICTI_t})$

Figure 4: Effect of Financial Development on Energy Transition



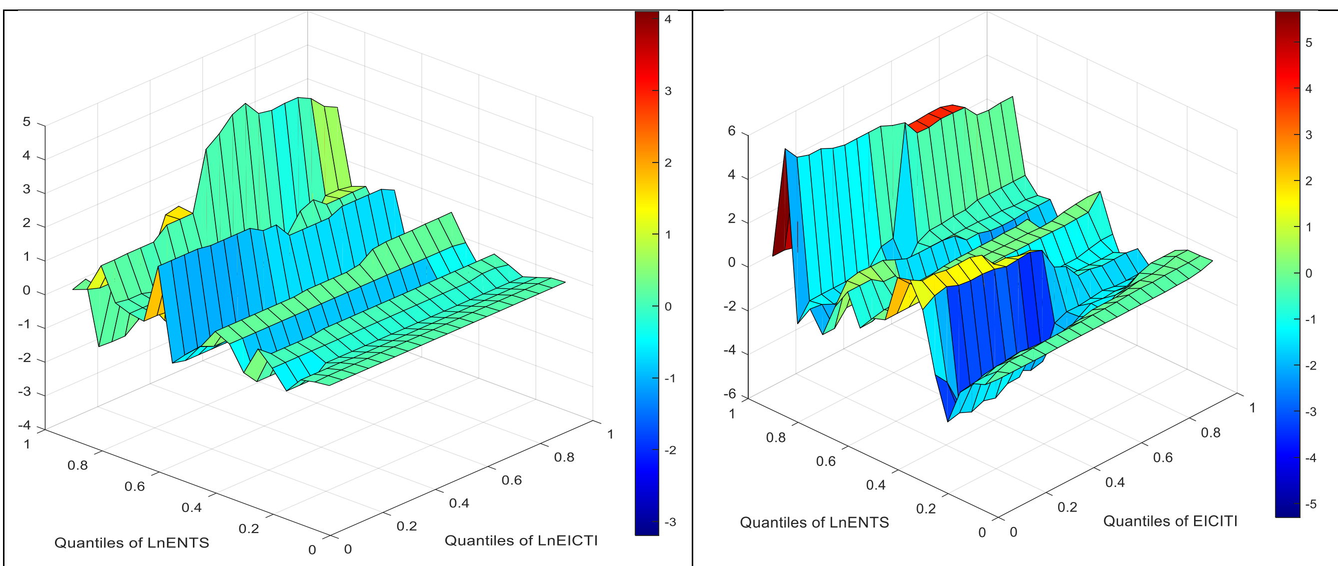
$ENT_t = f(GDP_t)$	$ENT_t = f(GDP_t, EPS_t, FD_t, HC_t, EICTI_t)$

Figure 5: Effect of Economic Growth on Energy Transition



$ENT_t = f(HC_t)$	$ENT_t = f(HC_t, EPS_t, FD_t, GDP_t, EICTI_t)$

Figure 6: Effect of Human Capital on Energy Transition



$ENT_t = f(EICTI_t)$	$ENT_t = f(EICTI_t, EPS_t, FD_t, GDP_t, EHC_t)$

Figure 7: Effect of Environmental related ICT innovations on Energy Transition

Figure 7 presents the influence of EICTI on sustainable energy (ENT) in the United States, considering the influence of FD, EPS, GDP, and HC. In the lower extreme tails (0.1-0.20), environmental ICT innovations have a positive impact on sustainable energy. The effect is negative within the 0.25–0.40 quantile range but turns positive in the middle and upper quantiles (0.50–0.95). This implies that environmental ICT innovations contribute positively to sustainable energy across most quantiles. This result is expected as innovation leads to the creation of more efficient and cost-effective green energy solutions. Advancements in technologies such as wind turbines, solar panels, biofuel processes, and energy storage devices have substantially enhanced the affordability and performance of clean energy sources [23]. As highlighted by [21] advancements in clean energy technology have led to cost declines. This decline in costs has made green energy systems more competitive with traditional energy sources like fossil fuels. As a result, individuals and companies find it economically viable to transition to green energy alternatives, which in turn promote greater utilization and adoption of renewable energy. Additionally, [25] emphasizes that innovation stimulates the emergence of innovative financing options such as crowdfunding, impact investments, and green bonds. Our findings are consistent with the research conducted by [24] which revealed that innovations contribute to raising environmental awareness among individuals and businesses, resulting in an increased demand for renewable energy. Similarly, the study conducted by [22] also documented that innovation brings about more sustainable and environmentally friendly energy options, leading consumers to become more conscious of their energy choices.

4.5. Robustness Test Results

The study utilized quantile regression to assess the reliability and consistency of the QQR, as illustrated in Figure 8. The results of the QR and QQR estimates indicate that the impact of environmental policy stringency on sustainable energy is consistent, suggesting the robustness of our findings (see Figure 8a). Both estimators show a positive relationship between the variables. Furthermore, Figure 8b compares the QR and QQR estimates for the effect of financial development (FD) on sustainable energy. The results demonstrate that in the lower quantiles, FD has a positive impact on sustainable energy, while in the middle and higher quantiles, the effect becomes even more pronounced, indicating a significant increase in sustainable energy. Similarly, Figure 8c presents the QR and QQR estimates for the effect of economic growth on sustainable energy, showing a positive association in each quantile. The QR and QQR estimates for human capital effect on sustainable energy (Figure 8d) display a consistent positive trend from the lower to upper quantiles. Finally, Figure 8e depicts the estimates of QR and QQR for the effect of environmental ICT innovations, with consistent positive results across all quantiles.

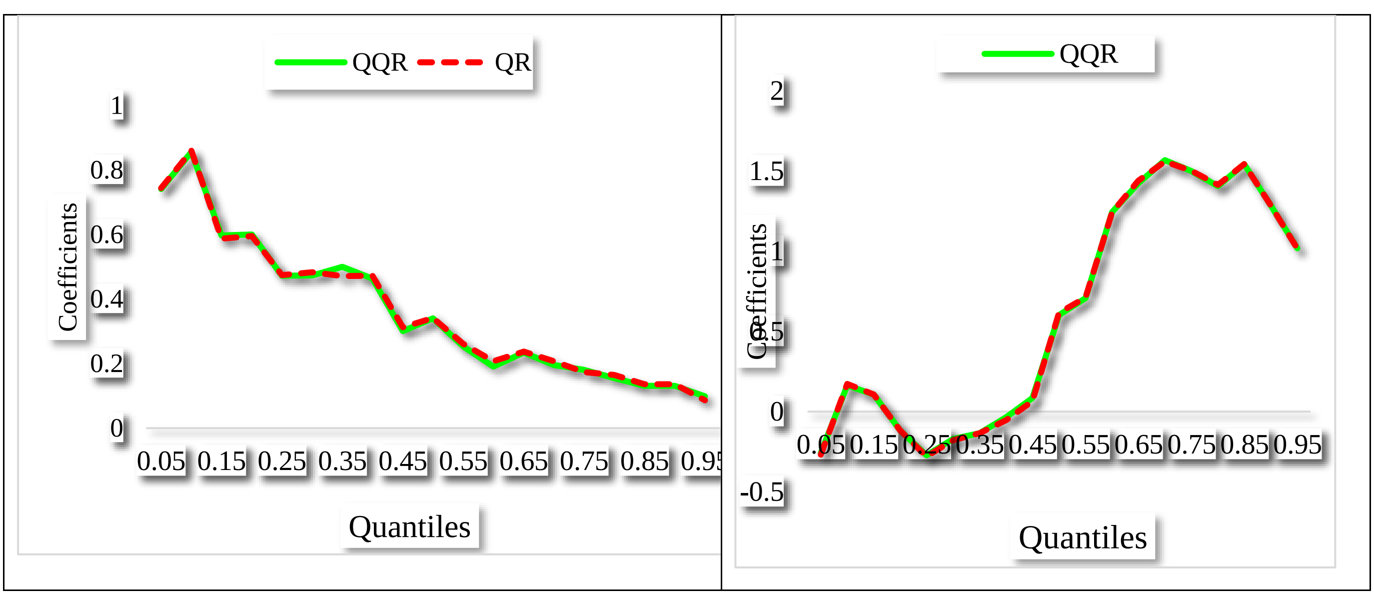
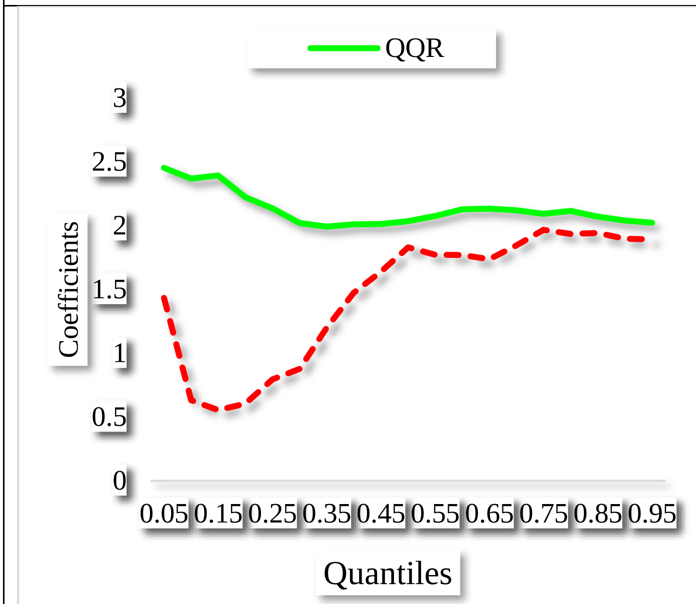


Figure 8a: Effect of Environmental Policy Stringency on Energy Transition

Figure 8b: Effect of Financial Development on Energy Transition



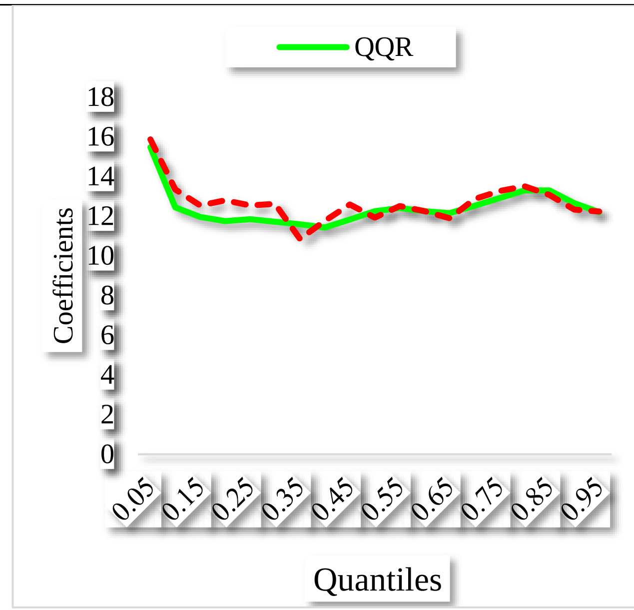


Figure 8c: Effect of Economic Growth on Energy Transition

Figure 8d: Effect of Human Capital on Energy Transition

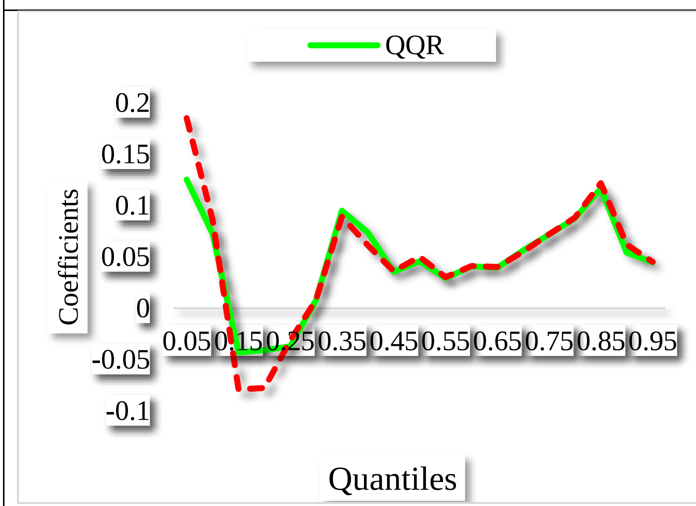


Figure 8e: Effect of Environmental related ICT innovations on Energy Transition

4.6. Nonparametric Quantile Causality

The study observed the causal interrelationship between the independent variables and sustainable energy across different quantile distributions of sustainable energy. Figure 9a presents the quantile causality in terms of both mean and variance, specifically focusing on the causal link from environmental policy stringency to sustainable energy. The analysis revealed causality in the middle quantiles (from 0.45 to 0.75) in terms of mean causality. Additionally, the results of variance causality demonstrated that environmental policy stringency can predict sustainable energy across the entire quantile distribution, with statistical significance at both the 5% and 10% levels. This means that advances in environmental policy stringency result in more effective surveillance and oversight of renewable energy systems, allowing for improved utilization and integration of clean sources of energy. This, in turn, may encourage the use of clean energy. This result is comparable to the result generated by the studies of [28] and [18].

Figure 9b shows causality from FD to sustainable energy in the USA. As clearly observed, the results of the causality in mean failed to refute the Ho hypothesis, thus, FD does not have predictive power over sustainable energy in mean. However, the result of the causality in variance shows that FD has predictive power over sustainable energy in middle tails specifically 0.35-0.55 quantiles at significance level of 5% and 10%. This indicates that the level of financial development can serve as a predictor of renewable energy consumption. Consequently, any changes or shifts in financial development policies are likely to significantly impact the utilization of clean energy resources. The causality results from economic growth to sustainable energy in the United States are presented in Figure 9c. Both the mean and variance causality analyses reveal similar findings, indicating that sustainable energy can be predicted by economic growth, particularly in the middle tails (quantiles 0.40-0.55). This supports the findings of previous studies [7], which also highlighted the role of economic growth in forecasting sustainable energy. In summary, policies aimed at promoting economic growth are likely to have a significant impact on the development of sustainable energy.

The causality analysis from human capital to sustainable energy yields interesting results, as shown in Figure 9d. Specifically, there is no evidence of causality in the mean from human capital to sustainable energy. However, in the quantiles 0.25-0.55, human capital can predict sustainable energy at a significance level of 5% and 10%. These findings align with similar conclusions reported in the studies of [22] and [45]. Moving on to Figure 9e, it depicts the causality from environmental ICT innovations to sustainable energy in terms of both the mean and variance. The mean causality analysis does not provide evidence of causality across the quantile distribution of sustainable energy, thus failing to reject the null hypothesis of "no causality exists". However, the variance causality results indicate that in quantiles 0.25-0.55 of the sustainable energy distribution, environmental ICT innovations can forecast sustainable energy. These outcomes are consistent with the studies of [24] and [46] which also documented causality from environmental ICT innovations to sustainable energy.

5. CONCLUSION AND POLICY SUGGESTION

5.1. Conclusion

The United States has been a focal point in empirical investigations on the influence of financial development, environmental policy stringency, human capital, and economic growth on sustainable energy. Previous studies in the United States have predominantly utilized conventional linear methodologies. However, recent research has highlighted the likelihood of nonlinear behavior in many time-series variables. Recently, the recognition of nonlinear effects has also gained prominence. Therefore, this study employed quantile-based approaches, such as nonparametric quantile causality, quantile cointegration, quantile-on-quantile regression, and quantile regression, to account for potential nonlinearities and capture a more comprehensive understanding of the interrelationships. Furthermore, we applied the recursive cross-quantilogram approach. The findings from the multivariate quantile-on-quantile regression demonstrate the positive influence of financial development, economic growth, environmental policy stringency, environmental ICT innovations, and human capital on sustainable energy across all quantiles. Furthermore, the nonparametric quantile causality analysis indicates that all the independent variables have predictive power for sustainable energy across the entire range of quantiles.

Additionally, outcomes from the recursive cross-quantilogram analysis consistently demonstrate substantial positive (negative) correlations at the 0.1, 0.5, and 0.90 quantiles across the entire study duration.

Figure 9a: Causality from Environmental Policy Stringency to Energy Transition

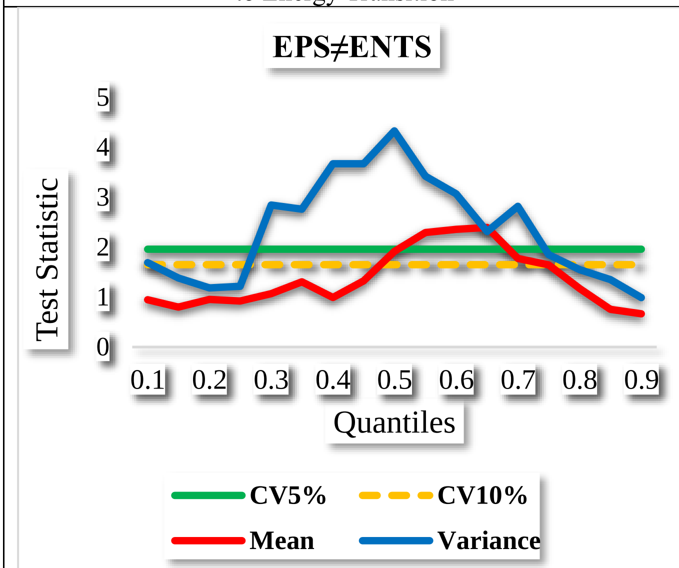


Figure 9b: Causality from Financial Development to Energy Transition

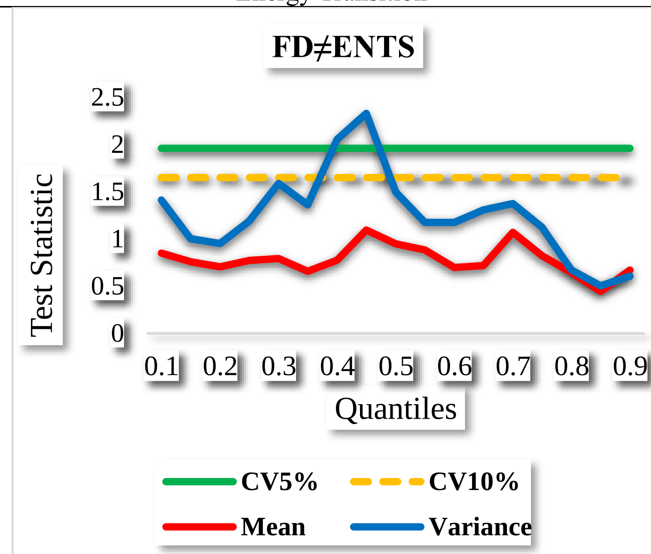


Figure 9c: Causality from Economic Growth to Energy Transition

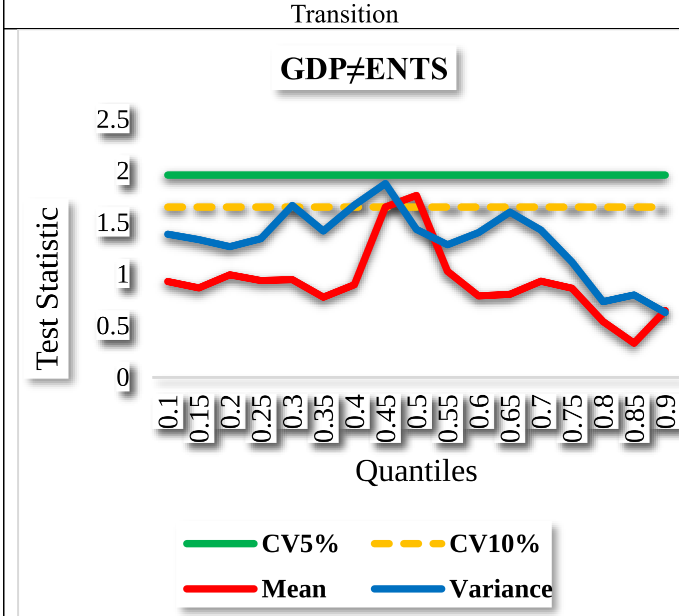


Figure 9d: Causality from Human Capital to Energy Transition

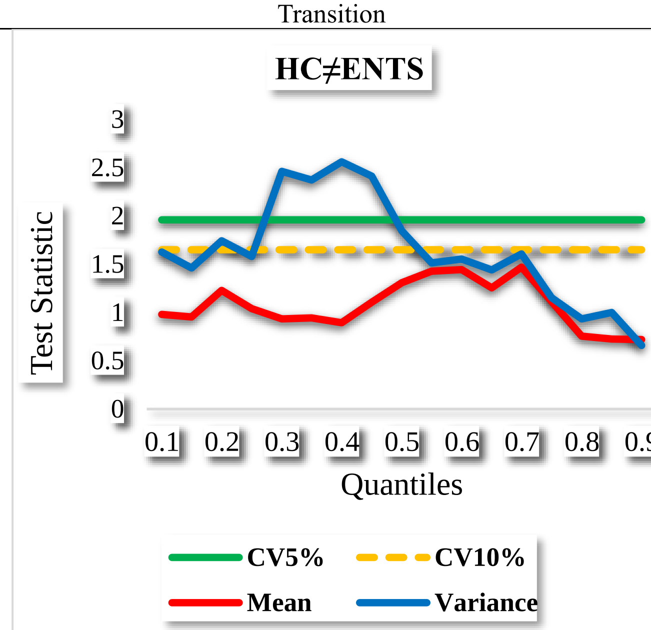
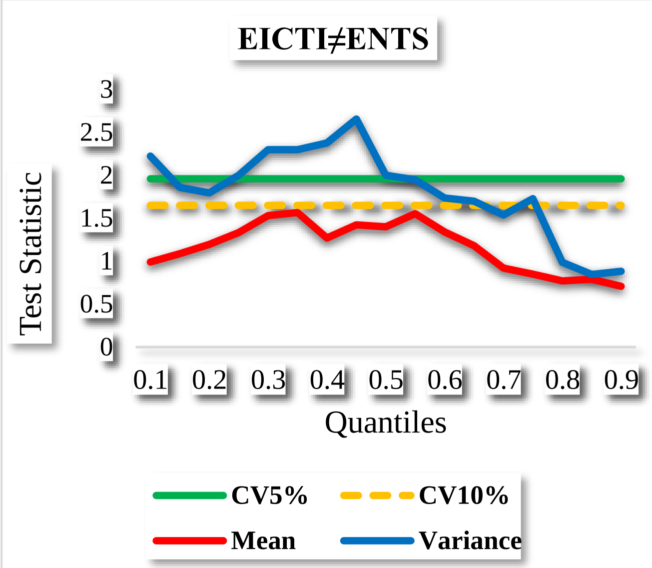


Figure 9e: Causality from Environmental related ICT innovations to Energy Transition



5. Policy Suggestions

Considering the positive impact of financial development on sustainable energy across all quantiles, it is essential for the United States government to prioritize enhancing access to affordable financing options for sustainable energy investments. This can be accomplished by facilitating favorable loan terms, establishing offering loan guarantees, specialized green banks, and promoting collaboration between financial institutions. Moreover, it is essential for the United States government to enforce and implement stringent environmental initiatives that stimulate the widespread utilization and acceptance of sustainable energy. These measures may encompass renewable portfolio requirements, targets for promoting green energy generation and emissions standards. To guarantee their effectiveness, regular stringent enforcement and monitoring of these initiatives are essential to foster an environment conducive to the integration and consumption of sustainable energy sources.

Given the positive interrelationship between environmental ICT innovations and sustainable energy across quantiles, it is imperative for the government to foster a supportive environment for research and development in this field. The government can offer support via grants, collaborations between research institutions, funding programs, and technology companies. By enhancing human capital through training and education, a larger workforce of skilled professionals capable of driving renewable energy initiatives and advancements will be available, contributing to the overall growth and success of the sector. Lastly, it is crucial to implement initiatives centered at initiating public awareness programs to educate the general population about the sustainable energy benefits and the importance of its usage. This can be attained via various means, such as organizing seminars and workshops, spreading information via different media networks, and involving organizations and community groups. By fostering a sustainable energy culture, the United States government can garner public support and inspire individuals to adopt green energy technologies in their daily lives, leading to widespread adoption and increased utilization of sustainable energy sources.

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Conflicts of Interest: The author declares no conflicts of interest
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Data Availability Statement: Data will be provided based on request

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