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Reimagining Energy Futures: The Role of Nuclear Power, Green Growth, and Government Effectiveness in Sustainability

Abstract

This study explores how nuclear power can shape the future of energy systems in the United States, with a focus on green growth, energy efficiency, and government effectiveness. The main goal is to examine how factors like load capacity factor (LCF), green growth (GRG), nuclear energy consumption (NEC), government effectiveness (GVE), and environmental policy stringency (EPST) contribute to sustainable energy outcomes. Using a unique empirical approach that combines Multi-variate Quantile-on-Quantile Regression (M-QQR) with Quantile-on-Quantile Granger Causality (QQGC) tests, this research uncovers complex, nonlinear interactions and causal relationships between these elements. The results show that green growth positively influences LCF, especially in areas with significant renewable energy investments. Additionally, effective government actions and stringent environmental policies are crucial for improving energy systems and boosting efficiency. Nuclear energy consumption plays a key role in enhancing energy reliability and performance. The study concludes with policy recommendations that stress the importance of strengthening government effectiveness and implementing stricter environmental policies to increase LCF, which is vital for creating a more sustainable and resilient energy infrastructure in the U.S.

Keywords: Green growth; government effectiveness; nuclear energy; M-QQR; USA

1. Introduction

Environmental degradation has become one of humanity's most serious threats, touching almost every area of human life, from public health and economic development to global security. The growing signs of climate change, deforestation, loss of biodiversity, and pollution emphasize the necessity of creating sustainable new models for such growth. Human activity has primarily caused environmental destruction, especially over-industrialization, depletion of resources, and unsustainable consumption. According to the Intergovernmental Panel on Climate Change (IPCC), these challenges demand a global response emphasizing the development of greener technologies, sustainable practices among industries, and effective climate policy implementation (IPCC, 2024). As one of the largest carbon emitters and producers, the US faces distinct challenges in achieving sustainable growth and transitioning to new energy sources.

In the United States, environmental degradation has been worsened by a historical reliance on fossil fuels, industrial processes that emit greenhouse gases, and an energy grid reliant on non-renewable resources. It is a significant energy consumer, one of the world's largest producers and users of electricity. Energy production, particularly electricity, primarily relies on coal, natural gas, and nuclear energy, accounting for around a third of total U.S. energy consumption (U.S. Energy Information Administration (EIA, 2025). While there has been real progress in deploying renewable energy sources like wind and solar, the real question is how to balance energy security and environmental security. Load Capacity Factor (LCF) is an important metric for understanding the efficiency of energy production. It has the potential to contribute significantly to U.S. energy goals of increasing energy security and grid reliability while decreasing carbon emissions (Caglar et al., 2023). The Load Capacity Factor (LCF) quantitatively represents the effectiveness and reliability of such energy systems. It is the ratio of the actual energy that a plant or a system produces to the maximum theoretical energy it could produce under biennial conditions (U.S.

Energy Information Administration, (EIA, 2025). More accurately, an increase in LCF means that an energy facility generates electricity more efficiently, thus increasing the power grid's overall performance. In the U.S., this is particularly key given that boosting energy efficiency is necessary for decarbonizing the economy and encouraging sustainable growth (M. I. Ali et al., 2025a; Kartal et al., 2023).

A critical element of enhancing LCF in the U.S. will be expanding the penetration of low-carbon energy sources while reducing waste and inefficiency in existing systems. According to Lyu et al. (2023), adopting advanced technologies, optimizing grid operations, and implementing strategic policy interventions can improve LCF significantly and increase the reliability of the energy system. The coupling of renewable energy systems (e.g., solar or wind) and conventional sources (e.g., nuclear power) may stabilize energy generation and thus reduce LCF by making the power grid more reliable (M. Ali et al., 2025). However, LCF's improvement depends on a more complex solution. It is about improving the efficiency of energy systems and creating an enabling environment through implementing policies promoting cleaner, more efficient energy technologies. Government effectiveness and policy stringency co-store significantly influence the trajectory of energy transformation in the USA (Teng et al., 2024a).

Nuclear energy is one of the most reliable and consistent sources in the U.S.. It can drastically improve LCF, mainly since it can produce vast amounts of electricity with a very reasonable greenhouse gas output. Nuclear power plants tend to have high capacity factors, often greater than 90% due to the continuous operation and base load electricity demand International Atomic Energy Agency (IAEA, 2020) nuclear is one of the few energy sources that can deliver the reliable, large-scale electricity needed to power a growing economy while limiting environmental degradation. This adds value to nuclear energy as an LCF booster that assists the transition toward a low-carbon energy grid. The role of nuclear power in reducing LCF is vital because it aligns with decreasing the carbon footprint of the U.S., which has some of the highest greenhouse gas emissions in the world, further contributing to climate change. Since nuclear energy is, by definition, low-carbon, if all of the fossil fuel-based generation were replaced by nuclear power, this would cause a dramatic decrease in the carbon intensity of the U.S. energy system (Hjelmeland et al., 2025). Furthermore, nuclear power can serve as a stable energy source that complements intermittent renewables such as solar and wind (U.S. Department of Energy (Elwell & Karen, 2012), and helps stabilize the grid and reduce the overall variability in power generation (Zahedi yeganeh et al., 2025). Although nuclear energy has enormous potential for LCF, it has challenges. Public perception, safety concerns and the high up-front costs of nuclear plants have been significant barriers to the growth of nuclear energy in the U.S. Progress in this area is being made through advances in nuclear technology, such as small modular reactors (SMRs), that are working to overcome these obstacles and position nuclear energy as a viable option for the generations ahead (IAEA, 2020).

As the U.S. energy transition unfolds, nuclear energy is a cornerstone of the low-emissions transition and of green growth more broadly. Green growth is defined by the Organization for Economic Co-operation and Development (OECD) as the process of achieving economic growth alongside environmental sustainability. These include the green economy, which seeks to conserve the environment and use resources efficiently while stimulating innovation and development (Gao et al., 2024). Including nuclear energy in the United States' energy mix aligns with green growth principles, with an ideologically valid provision of a low-carbon energy supply that can support the energy demand of economic development. The high capacity factor of nuclear energy shows that it is an asset of a green growth strategy, where it allows the assurance of energy supply by reducing the dependency on fossil fuels, and the increased integration of renewable energy sources in our grid (Cheng et al., 2025). Further, nuclear can be a well-suited tool to help the U.S. climate targets because it can significantly decrease greenhouse gas emissions from the electricity sector, where it creates a significant share of overall emissions (U.S. Environmental Protection Agency (EPA, 2021).

The government effectiveness and policy stringency are essential in determining the future of energy systems and LCF in the U.S. Effective governance guarantees that policies will also improve energy efficiency and uphold clean technologies rather than well-designed " (Wang et al., 2025). In order to achieve LCF carbon-free generation, policy instruments such as encouraging investment in renewable energy sources, energy efficiency, and expanding nuclear energy can substantially impact LCF by accelerating technological advancements and contributing to carbon emissions mitigation (Feng et al., 2024a). In addition, the compatibility of U.S. energy policies with the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), will play a significant role in ensuring the long-term sustainability of energy systems (López et al., 2025). The need for affordable, reliable, sustainable, and modern energy for all (Sustainable Development Goal 7, SDG 7) can only be achieved through a good mix of energy sources, including nuclear, and energy literacy, which means energy production security and environmental protection. Likewise, SDG 13 calls for urgent action to combat climate change, which enhanced LCF can address through lower carbon and higher energy sources such as nuclear power (Çamkaya et al., 2025).

This paper uniquely contributes to the literature on the USA's environmental sustainability and energy policy. First, it presents an innovative integration of green growth and nuclear energy, focusing on their linkages to the load capacity factor as a proxy for environmental quality. Nuclear energy's importance in energy transformation and eco-friendly growth is underscored by emphasizing this variable. Second, it examines the interaction between government effectiveness, environmental policy stringency, and the load capacity factor, which has seldom been explored in previous studies. This analysis helps evaluate the impact of political stability and strict environmental policies on energy system performance. Finally, we highlight novel insights into these associations using cutting-edge econometric techniques, such as Quantile-on-Quantile methods and the Quantile ADF and Quantile KPSS unit root tests. Moreover, Quantile-on-Quantile Granger Causality tests offer new information on causality dynamics across different quantiles, capturing the dependence structure in a segmented manner. This allows for a deeper understanding of the underlying interactions between these variables and how they change across levels. The combination of these methodological innovations significantly contributes to energy policy and econometrics.

2. Literature Review

2.1. Load capacity factor with green growth

Modern technology has been instrumental in stimulating economic growth in most societies and has contributed to industrial productivity and improvements in the standard of living. Nevertheless, the technology has resulted in various environmental issues, such as pollution, scarcity of resources, and climate change (Shahbaz et al., 2018). In the face of these pressing challenges, numerous international organizations and institutions, including the United Nations, have advocated Green Growth (GRG) as a model or approach committed to sustainable and environmentally sensitive economic development (Dam et al., 2024). Green growth advocates policies that pursue a growth path that balances economic development with conservation of the environment, emphasizing sustainable use of natural resources. Its purpose is to push economic growth without harming the environment even more, so the movement would impact more sustainable production and consumption models. By promoting policies that advance economic opportunity and protect the environment, green growth has a critical impact in addressing environmental harms and preserving the planet for future generations. It provides a blueprint for countries to support growth while strengthening the health of the environment as part of the overall goals of sustainable development.

Green growth is a new economic concept, which advocates achieving economic development while ensuring environmental sustainability. The role of LCF in green growth has gained attention, especially for the U.S. energy transition. With U.S. efforts to reduce carbon emissions and increase energy efficiency, green growth initiatives are also important for evolving energy system dynamics. The LCF is a ratio of actual energy output to maximum potential output, measuring energy efficiency for power plants. It has been observed in the literature that integrating renewable energy in generation portfolio gives rise to mixed effect on LCF. Wind energy systems, for example, will have higher LCF in regions with stable wind patterns, whereas solar energy systems will have lower LCF based on sunlight availability. However, LCF improves considerably when renewable integration is combined with energy storage technologies and grid modernization, thus assisting the long-term sustainability of all green growth initiatives. As such, green growth policies typically incentivize developments in energy storage technologies, grid stability, and renewable energy technologies. In previous studies, some researchers have not considered green growth as an independent variable but have focused on it as a dependent variable; however, such studies are rare , except for (Razzaq et al., 2021) and (Wang et al., 2024), which specifically examined its influence on environmental goals. However, there is a lack of empirical analysis on the linkage between GRG and load capacity factor. The connection between GRG and load capacity factor (LCF) is , in particular, far from being adequately studied in the existing literature. This study seeks to contribute to this gap by providing new empirical contributions on the complicated interplay between GRG and LCF. By exploring this underexplored link, this study aims to advance our knowledge on how GRG might impact long-term environmental sustainability and inform policymakers and scholars interested in achieving sustainable development goals.

2.2. Load capacity factor relationship with nuclear energy

Nuclear energy is one of the few sources capable of continuous, base-load power generation, leading to higher LCF than other energy sources. A study by Aydin et al. (2023) investigates the LCF of nuclear plants in the United States and finds that nuclear plants tend to be high-capacity users, with LCF values typically around 90-95%. This contributing factor of operational efficiency comes mainly from the capacity of nuclear plants to operate continuously for extended periods without the need to take time off, like the dependence of renewable sources on weather. Nuclear energy has a demonstrated LCF, but high upfront capital costs, regulatory barriers, and environmental opposition limit its growth. Wang et al., (2024) discuss these challenges as they apply to the U.S. nuclear sector and argue that while new nuclear plants could support improvements to national LCF, doing so will require overcoming various barriers. The paper concludes that safety measures that strengthen the perception of nuclear power, as well as reducing regulatory constraints and investment in outreach campaigns, can help build public trust in nuclear power and speed up approvals for new plants. Moreover, the economic viability of nuclear power will increasingly come under pressure from the price competitiveness of renewable energy technologies. Michaelides et al. (2020) found that new nuclear power plants find it difficult to compete economically, which can decrease the total low-carbon fraction (LCF) of the grid if renewables “crowd out” nuclear generation. This tension illustrates the contradictory impacts of nuclear energy usage on high LCF achievement alongside the financial and regulatory barriers to high nuclear energy production. Despite these challenges, nuclear energy is important to the U.S. energy mix. Raihan et al. (Raihan et al., n.d.) emphasized that nuclear energy has to be included within the diversified energy portfolio and renewables to ensure high LCF in the future.

2.3. Load capacity relation with Government Effectiveness

Recent academic dialogues have focused more on the relationship between the quality of governance and environmental outcomes, mainly measured in terms of carbon emissions, climate action and progress toward the Sustainable Development Goals (SDGs) (Feng et al., 2024a; Oyewo et al., 2024) with a few exceptions where the emphasis on CO_2 emissions, however, the most recent studies have moved beyond the center and have taken consideration of comprehensive ecological indicators such as the Load Capacity Factor (LCF), which has been defined as the environmental sustainability index by comparing the biocapacity (regenerating resources) with the ecological footprint (Pata et al., 2024). It is an important determinant of how much a country can develop or maintain an environmental policy that will contribute to the LCF. Good governance allows for stringent environmental legislation, eases the transition to renewable energy sources, and incentivizes the sustainable use of land – all of which expand biocapacity and reduce ecological damage (Zhang et al., 2024). Empirical studies suggest that a country with a more efficient government is more likely to have better environmental commitment, reflected in the direction and pace of LCF. For instance, Pata et al. (2024) proved that efficiently governed GCC countries not only managed to enhance their LCF but also caused a reduction in their ecological footprints and increased biocapacity through reforestation and sustainable farming. Similarly, Isik et al. (2024) identified that, in G-7 economies, better government effectiveness is associated with

LCF growth, where the effect is primarily explained by the strengthening of climate regulations and the new clean energy investment. On the other hand, emerging countries with weak governance usually face reduced LCF due to the lack of legal enforcement, corruption, and poor implementation of policies (Dincă et al., 2022). For example, there is evidence of deteriorating LCF trends in sub-Saharan Africa, where governance is weaker due to uncontrolled deforestation, high dependence on fossil fuels, and limited institutional coordination (Oyewo et al., 2024). Despite LCF being a more comprehensive sustainability assessment, it is outnumbered by the investigations focusing on CO_2 emissions (Islam et al., 2022; Pata et al., 2024).

2.4.Literature Review Gap

This work analyzes the literature on LCF and its connections with green growth, nuclear energy, government effectiveness, stringency-related policies, and gaps in existing studies. First, while there is considerable literature on green growth and renewable technology, much less research explores how green growth policies impact LCF across diverse energy systems. This means there is also a lack of studies analyzing the LCF in regions such as California and Texas, where renewable penetration differs. However, the policies in place in the different states are the same. More empirical research on optimizing LCF in energy systems across different countries with technology discovery and grid integration is needed in the future. Second, although some acknowledge nuclear energy's important role in the LCF sectoral improvement, there is insufficient engagement with the underlying economic, political, and regulatory barriers to its build-out and the limited prospects for its continued competition with ever increasingly inexpensive renewables. Further studies are required on the role of green growth and regulatory bottlenecks on the contribution of nuclear energy to LCF, as well as the optimization of existing nuclear facilities with high LCF. Third, government effectiveness pays close attention to LCF; existing studies primarily deal with policy impact while neglecting the dynamic relationship of government quality, institutional capacity, and LCF. Research exploring how synergies between government effectiveness and technological innovation are employed to optimize energy systems seems lacking at the state and federal levels. Finally, existing Load Capacity Factor (LCF) studies mainly utilize conventional frameworks like linear regression models and simple unit root tests that may miss the complex non-linear dynamics of various energy systems. One significant gap in this work is the relatively rare application of novel quantitative techniques to show these, namely the Quantile on Quantile (QQ) and the Quantile Augmented Dickey-Fuller (QADF) test, as well as the Quantile Kwiatkowski-Phillips-Schmidt-Shin (KPP) unit root test, Quantile-on-Quantile Granger Causality (QQGC). These sophisticated techniques offer a more comprehensive examination of the association between LCF and important predictors like green growth, nuclear power, and governance by addressing heterogeneity across multiple quantiles of the data distribution. In addition, the QQ method provides a more detailed exploration of the LCF underlying factors. At the same time, the QADF and Quantile KPP unit root tests focus on non-stationarity and structural breaks which is potent when analyzing time series datasets in energy systems. Adopting these new techniques allows for improved methodologies to combat the shortcomings of traditional LCF methods, providing a deeper understanding of the eventual role of LCF in the energy transition.

3. Variables Configuration and Base Model Development

3.1. Theoretical framework

Economic growth plays a two-sided role in shaping ESG performance. While it can provide more resources for sustainable development, unchecked and rapid growth may actually hinder environmental goals, leading to increased emissions and greater social inequalities (Işık et al., 2025a). We explore the data-driven, empirical association of load capacity factor (LCF) and green growth in a national setting within the United States, interacting with government effectiveness, nuclear energy, and environmental policy stringency. The US was chosen for this study because of its profound impact on world energy production and environmental policy. Uncertainty in climate policy makes it harder for companies to invest in sustainable practices. With unpredictable regulations, businesses often delay adopting green technologies or scale back their ESG efforts (Işık et al., 2024b; Islam et al., 2025). As one of the world's largest economies and energy producers, the U.S. has taken significant steps to integrate more renewable energy into its grid while continuing to push nuclear energy production to the forefront. As part of this commitment, the country has signed onto international climate agreements, and its energy policies have aligned with global sustainability targets like the Paris Agreement's goal to decrease greenhouse gas emissions and increase the share of renewable energy (EPA, 2021). Moreover, the U.S. has prioritized the diversification of its energy sources and the reduction of its reliance on fossil fuels, both of which have spearheaded the expansion of nuclear energy capacity and green technology integration within the national grid.

However, the United States, despite this progress in renewables and nuclear, would still face formidable challenges as needed green growth goes far beyond overcoming the problems of environmental destruction. As energy prices go up, they can encourage the use of renewable energy and more efficient technologies, which is great for the environment. However, this can also put pressure on industries, sometimes causing short-term governance challenges (Işık et al., 2025b). This seemingly paradoxical trend, where such large amounts of energy infrastructure investments are associated with inequitable environmental benefits, has generated substantial interest in the academic literature. Given that from the analysis of (Hassan et al., 2023), the U.S. is a leader in the transition to renewables, but the net benefit in the transition to renewable energy is still region-specific, and according to the level of government effectiveness and enforceability of transitions, the U.S. demonstrates uneven ratios of greenness in growth. The impact of ESG factors can differ by sector. In developing regions, technology and governance factors often boost growth, while in high-pollution industries, environmental policies may slow down development (M. I. Ali et al., 2025b; Işık et al., 2024a). Given this, the study explores how government effectiveness, nuclear energy adoption, and environmental policy stringency influence the pursuit of green growth in the U.S.

3.2. Data Sources

Detailed data description of investigated variables, time frame 1995Q1-2022Q4 for USA, Load Capacity Factor (LnLCF) is calculated by dividing biocapacity by ecological footprints, offering insight into the sustainability of resource use within a specific region. This data is sourced from the Global Footprint Network (GFN). This study regards the green economy as an important control variable, with its measurement represented by green GDP (gross domestic product). Through the lens of ecological concerns, the goal is to embed environmental considerations into economic theories to facilitate worldwide sustainable development. Crucial factors, such as resource consumption, waste pollutants, and CO_2 emissions, significantly affect climate and GDP. This is why green growth emerged, which is estimated by adjusting conventional GDP for environmental costs. Green growth is calculated by subtracting the environmental implications from conventional GDP to better measure sustainable growth in real terms. The green growth is calculated using data from the Organization for Economic Co-operation and Development (OECD). Nuclear energy consumption (LnNEC) refers to using nuclear energy as a clean source for electricity production, according to data provided by British Petroleum (BP). This variable

Table 1: Data Sources

Variables	Acronym	Definition	Data Sources
Load Capacity Factor	LnLCF	Load Capacity Factor = Biocapacity ÷ ecological footprint.	GFN (2024)
Green Growth	LnGRG	The green economy uses the green GDP (green gross domestic product). We computed the green GDP by subtracting the values of the specified components from the conventional GDP, resulting in a more precise representation of sustainable green growth.	OECD (2024)
Nuclear Energy Consumption	LnNEC	Nuclear energy is used as a clean source for nuclear electricity production.	British Petroleum BP (2024)
Government Effectiveness	LnGVE	This report reflects perceptions of the quality of policy formulation (economic, social, and environmental) and implementation and the credibility of the government's commitment to such policies.	WDI (2024)
Environment Policy Stringency	LnEPST	The index is based on the degree of firmness of 13 environmental policy instruments, principally connected to climate and air pollution.	OECD (2024)

measures how much nuclear energy is consumed as part of the total energy mix, reflecting the role of nuclear power in a country's clean energy strategy. Government Effectiveness (LnGVE) captures perceptions of the quality of government policies in terms of formulation and implementation and the credibility of governmental commitments to these policies. This data, reflecting the governance quality in various countries, is sourced from the World Development Indicators (WDI). Finally, Environment Policy Stringency (LnEPST) is an index that quantifies the firmness of environmental policies, particularly those linked to climate change and air pollution, based on 13 key policy instruments. This index, sourced from the OECD (2024), evaluates national environmental regulations' strictness and enforcement mechanisms. These variables play a crucial role in assessing the broader economic, environmental, and governance factors that influence sustainability and development outcomes. The detailed investigated variables, along with their data descriptions, are documented in Table 1.

3.3. Model construction

Now we construct the following simple model to focus on the primary purpose:

$$LnLCF = f\,(LnGRG, LnGVE, LnNEC, LnEPST) \qquad \text{Eq.1}$$

Eq.(1) can be improved in the following way;

$$LnLCF_t = \varphi_0 + \varphi_1 LnGRG_t + \varphi_2 LnGVE_t + \varphi_3 LnNEC_t + \varphi_4 LnEPST_t + \tau_t \qquad \text{Eq.2}$$

In Eq. (2), the regression coefficient on other existing attributes is specified with a vector presenting the coefficient of the variables examined, to which is the unobserved impacts of outside inducements as a disturbance term. In this section, we investigate the potential effects of each coefficient in light of the development of the literature. Regarding the role of Green Growth (GRG), we hypothesize that nations with a higher commitment to Green Growth policies will exhibit improved environmental performance and sustainable development outcomes. This may be reflected in a positive effect on the Load Capacity Factor (LCF), which indicates the efficiency and resilience of power systems in supporting sustainable energy solutions, $(\varphi_1 = \frac{\Delta LnGRG_t}{\Delta LnLCF_t} > 0)$.

Concerning Government Effectiveness (GE), we hypothesize that nations with higher government effectiveness will exhibit improved management and operational efficiency within their energy systems, as reflected in the Load Capacity Factor (LCF). The enhanced governance is expected to lead to better infrastructure development, policy implementation, and overall system resilience, thus positively influencing the LCF. Consequently, we predict a positive, non-negative relationship between Government Effectiveness and Load Capacity Factor, where higher GE enhances energy system performance and contributes to sustainable development outcomes. This hypothesis $(\varphi_2 = \frac{\Delta LnGVE_t}{\Delta LnLCF_t} > 0)$ suggests that better government effectiveness can improve the operational capacity of the energy grid and promote sustainable development by improving efficiency, resilience, and infrastructure. We hypothesize that increased Nuclear Energy Consumption (NEC) in the USA will positively impact the Load Capacity Factor (LCF). Since nuclear energy offers a stable and reliable power source, it is expected to reduce supply volatility and improve grid efficiency, thereby enhancing the LCF and supporting sustainable energy management, $(\varphi_3 = \frac{\Delta LnNEC_t}{\Delta LnLCF_t} > 0)$. We hypothesize that stronger environmental policies and higher policy stringency will positively influence the Load Capacity Factor (LCF). Stringent environmental policies are expected to drive the adoption of cleaner and more efficient energy technologies, which can enhance the reliability and efficiency of the energy grid. As a result, we predict that stricter environmental regulations will lead to a higher LCF, promoting sustainable energy systems and improving grid performance, $(\varphi_4 = \frac{\Delta LnEPST_t}{\Delta LnLCF_t} > 0)$.

3.4. Empirical Methodology

To solve the problem of stationarity, this study employs the innovative novel quantile Augmented Dickey-Fuller (QADF) and Quantile Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests, according to Adebayo and Özkan (2024). Assessing stationarity at various quantiles is powerful, and we must mention that the strength of these tests comes from their ability to look at the stationarity across quantiles to give you a deeper understanding of the behaviour of the data across its distribution, straight tail, fat tail, etc. This resultant strategy helps design the test by catering well with the condition of the heterogeneity existed in the data and captures the stationarity behaviors that the ADF and PP tests miss, while the non-linear dynamics of the selected variables are investigated through the Brock-Dechert-Scheinkman (BDS) test, proposed by Brock et al. (1996).

Once we had executed these first tests, we go on to benchmark our final regression model. As the independent and dependent variables may have different relationships depending on their quantiles because of the potential presence of non-linearity (Sim and Zhou, 2015), we try to focus on the relationship between the quantiles between the independent and dependent variable. This constitutes our motivation when using a non-parametric approach in Derived M-QQR which provides the reliable and robust results in linear or non-linear environments. Although (Sim and Zhou, 2015)original model is built upon a bivariate framework estimating the interaction of two variables, it does not include possibly relevant factors. If they are not taken into consideration, this introduces omitted variable bias (as explained in previous sections) which can end up exposing the estimates to endogeneity and result in violation of the conditions of OLS estimation. This caveat has been highlighted in earlier studies specifically referring to bivariate models (e.g., (Ashley et al., 1980). Thus, to fix this problem we extend the bivariate framework of (Sim and Zhou, 2015) by adding more exogenous variables turning the model into a multivariate one. This change provides an estimate of the average of the selection-adjusted relationship between the variables through the multivariate quantile-on-quantile regression (M-QQR) framework which resists omitted variable bias and endogeneity problems.

$$l_t = p^{\lambda}(c_t) + \sum\nolimits_n \omega^{\lambda}(J_t) + \sum\nolimits_n \pi^{\lambda}(c_t * J_t) + \tau^{\lambda} \qquad \text{Eq.3}$$

In Eq. (3) l is the dependent variable LCF, c is the independent variable and J is the vector of other explanatory variables and τ is an actual unobservable, λ-quantile disturbance term. Eq. (3) decomposes as follows:

$$l_t = \left(p^{\lambda} + \sum\nolimits_n \pi^{\lambda} J_t \right) c_t + \sum\nolimits_n \omega^{\lambda}(J_t) + \tau^{\lambda} \qquad \text{Eq.4}$$

$$l_t = v^{\lambda}(c_t) + \sum{}_n \omega^{\lambda}(J_t) + \tau^{\lambda}$$

τ^{th}

In Eq. (4) because the effect of the dependent variable on l are unmeasured, we estimated this by ν.λ. To ensure that there is a tail dependence between the τ^{th} of LCF and τth of the forecaster variable c, we use the first-order expansion of νλ. as follows:

$$v^{\lambda}(c_t) \approx v^{\lambda}(c^{\tau}) + \upsilon^{\lambda'}(c^{\tau})(c_t - c^{\tau}) \qquad \text{Eq.5}$$

The above mathematical form in Eq. (5) shows that νλct and νλ ′ cτ both have indices τ and λ while cτ has index τ. Furthermore, the first order expansion of πλ Jt is leads to the fact that πλJτ and πλ ′ Jτ are indexed by λ and τ as well. Based on the properties of the nested function, νλcτ and νλ′cτ, which are the nested functions of ρλ and ωλ Jt, can be expressed as v0λτ and v1λτ. From Eq. (4), we can write:

$$\underbrace{l_t = \upsilon_o(\lambda,\tau) + \upsilon_1(c_t - c^{\lambda}) + \sum{}_n \omega^{\lambda}(J_t) + \tau^{\lambda}}_{\Omega} \qquad \text{Eq.6}$$

In Eq. (6) where λ and τ are prediction and predicted variable quantiles (5-95%) respectively. Moreover, τλ in Eq. (6), where the disturbance term is in the sense of the 0 λ -quantile. Moreover, Ω within the complete equation represents the functional logic of the predictor characteristic over the predicted criterion in this model. On the basis of the initial model (Eq. (2) that isn't based in many variables quantile approach Eq. (2) cannot be used to flexible model for the unobserved heterogeneities that the covariates can share. Thus, we add an extension to our previous model (Eq. (2) and building a multivariate QQR model. In other words, we take the values of c1,c2……. cn are the predictor parameters and l is the response parameter. Pooling this information and shaping the quantile sequences_5th to_95th, abbreviated by _, we can express the multivariate QQR model as follows:

$$l_t = \upsilon_o(\lambda, \tau_1, \tau_2 ....\tau_n) + \upsilon_1(\lambda, \tau_1)\left(c_{1t} - c^{\lambda_1}\right) + \upsilon_2(\lambda, \tau_2)\left(c_{2t} - c_2^{\lambda_2}\right) + \\ ... + \upsilon_n(\lambda, \tau_n)\left(c_{nt} - c_n^{\lambda_n}\right) + \sum_n \omega(\lambda)(J_t) + \tau^{\lambda} \qquad \text{Eq.7}$$

In Eq. (7) above, τ1,τ2…….τn were respective quantiles of c1,c2…….cn, whereas λ reproduces the quantile of response variable l. Moreover, v1,v2……vn are the estimates of the corresponding quantiles of the predictor and predicted variables.

3.5. Robustness Confirmation: Quantile-on-Quantile Granger causality test

One of the robustness tests we adopt in our analysis was the quantile-on-quantile Granger causality (QQGC) test of Adebayo and Oktay, (2024). This is particularly valuable since QQGC test helps nothing to knowing if the causal dependence may differ all over the distribution (at all quantiles) of one variable, affecting the other. It also enables a more comprehensive investigation of causality, helping to uncover complex non-linear and asymmetric relationships that standard Granger causality tests are unable to find. Including QQGC into the mixer strengthens our analysis, and we are now able to investigate how variables interact with each other in a more elaborate form, by considering both variables distributions.

4. Results and Discussion

4.1. Preliminary Statistical and Diagnostic Results

Descriptive statistics of the variables are shown in Table 2. As observable, all the mean variables are positive except for "LnGRG" which is incredibly high meaning it carries outlier or possible data issue in it. It is evidenced that the LCF, median and mean are closed to each other which means that the probability of outliers in the data that is being analyzed is minimal. This indicates that the datapoints lie at an equal interval. The standard deviation values also do not suggest any outliers. In this sense, these values are not the dominant ones – the deviation of data points from a mean position is not very high. Thus, out of all the studied variables, "LnGRG" and "LnLCF" were characterized by the highest volatility, which is evidenced by the relatively high values of standard deviations.

We also reported the skewness and kurtosis tests results. All chosen variables except "LnGVE" and "LnEPST" assume negative values of skewness because most of data points are on the right of the distribution. The values for skewness also suggest that the distribution of the variables are not symmetrical, with "LnNEC" having the most extended right-tailed distribution. With the exception of "LnGRG," "LnLCF," and "LnNEC," which have relatively high kurtosis values, the remaining variables have fatter tails compared to others. We also perform the Jarque-Bera test for non-normality. Because the p-values value of the test statistics is greater than 0.05, we reject the null hypothesis of normality, and conclude that the operational parameters are not distributed normally. Therefore, the Jarque-Bera test results indicate that we need to resort to econometric methods that can accommodate the asymmetric characteristics of the chosen variables. Hence, alternative techniques such as quantile regression would help to uncover the asymmetric relationship between the variables over a range of heterogeneous quantiles.

Variables	Mean	Median	Min	Max	SD	Skewness	Kurtosis	JB
LnLCF	2.105	2.213	0.464	2.641	0.574	-2.242	7.271	70.111
LnGRG	3.644	1.338	1.264	1.858	2.602	7.141	54.010	49.858
LnGVE	1.512	1.521	1.217	1.740	0.138	-0.465	2.932	18.003
LnNEC	2.936	2.368	0.453	13.97	2.150	3.697	19.137	55.514
LnEPST	3.113	3.11	0.888	4.722	0.830	-0.418	2.781	16.097

The QQ plots shown in the Fig.1. In each plot we check for which variable pair, the theoretical quantiles are plotted against the sample quantiles. The red line shows the expected linear relationship of the variables if they have a normal distribution. The points in each of the plots conforms closely to the red line implies the variables are approximately normally distributed. The lines are surrounded with shaded areas, which represent the confidence interval, and we can see basically all variables follow the expected distribution.

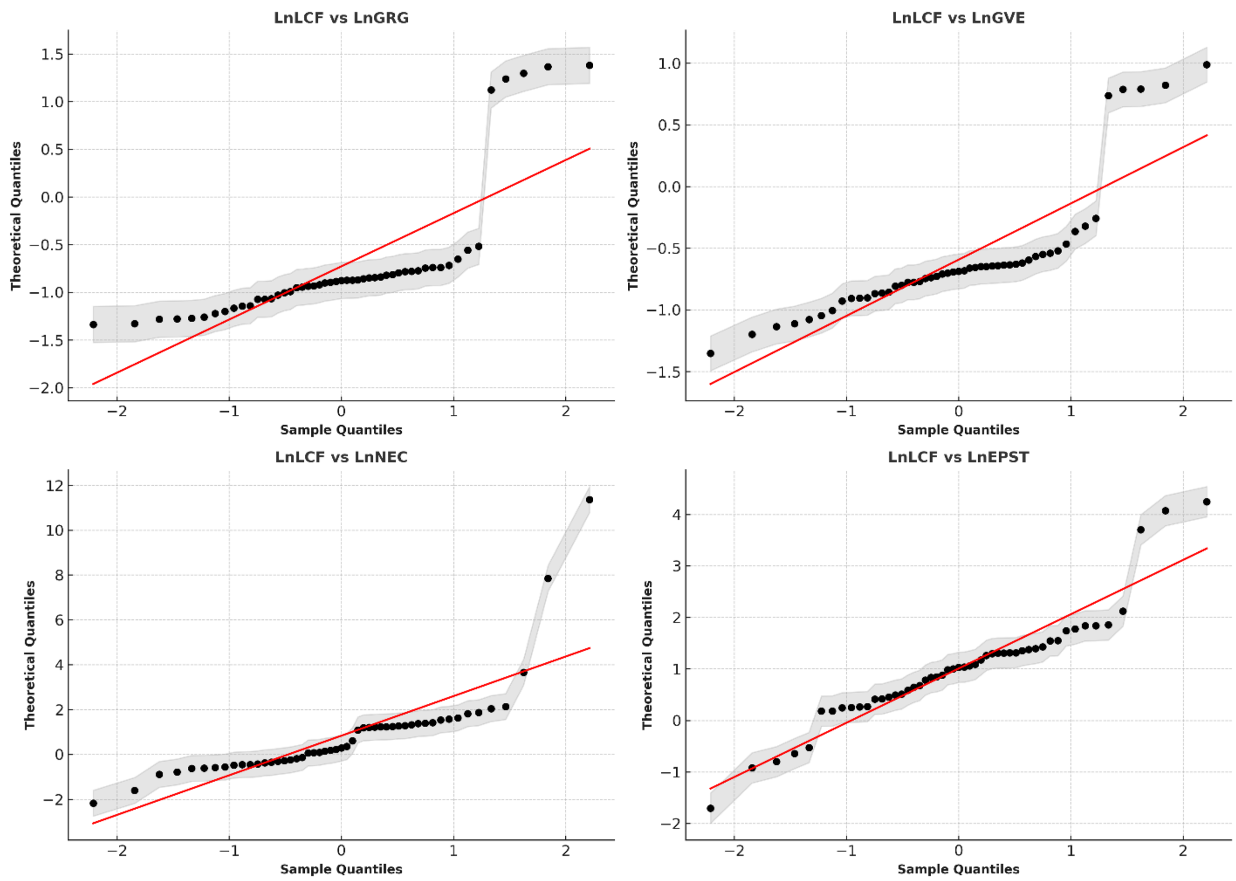

Fig.1 indicate QQ plot

Results from the BDS test demonstrate that all (LCF, GRG, GVE, NEC, and EPST) of the variables exhibit significant non-linear relationships at all embedding dimensions (M2, M3, M4, M5, M6) are shown in Table.3 and Fig.2. The "*" means the relationships are non-linear for sure (they are significant at the 1% level). Among all variables, LCF exhibits the most prominent non-linearity (across all the dimensions) with respect to the independent variable for each responsive variable in the higher-dimensional space (M4, M5, M6). As we increase the embedding dimension from M3 to M6, we observe a significant increase in the non-linearity of EPST. The bottom line is that non-linearity is a prominent feature of all variables we examined. The multivariate Quantile Regression (QQR) method can be helpful for modelling complex linear/non-linear relationships between the parameters underlying this non-linearity. By tracking the impact of independent variables at different quantiles of the dependent variable, QQR can give a deeper understanding of the non-linear relationship in the data and helps in a more holistic analysis.

Table 3: BDS Test Results for Non-Linearity Check

Dimensins	LnLCF	LnGRG	LnGVE	LnNEC	LnEPST
M2	0.103***	0.055***	0.077***	0.099***	0.103***
M3	0.158***	0.058***	0.098***	0.173***	0.158***
M4	0.200***	0.024***	0.118***	0.224***	0.270***
M5	0.218***	0.041***	0.117***	0.244***	0.218***
M6	0.231***	0.125***	0.147***	0.243***	0.231***

Note: *** shows level of significance at 1%

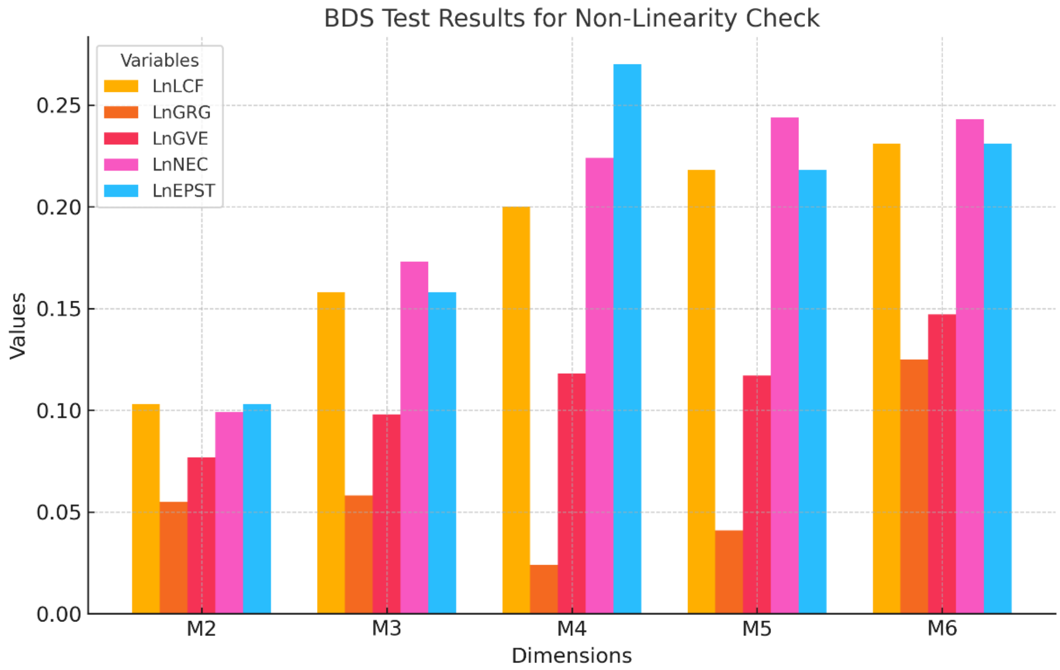

Fig.2 indicated the graphical representation of Non-linearity check

The correlation matrix shown in the Fig.3 illustrate the relationships between several main variables: load capacity factor (LCF), green growth (GRG), government effectiveness (GVE), nuclear energy consumption (NEC), and environmental policy stringency (EPST). The most noticeable observation is the very high negative correlation between LCF and GRG (-0.88) as one increases the other decreases. There is a moderate positive relationship with GVE (0.51) and weak positive with NEC (0.18). In contrast, LCF has subtle negative association with EPST (-0.16) GRG is moderately negatively correlated with GVE (-0.50) and shows almost no correlation with NEC. Rest correlations are weak or no correlations, GVE and NEC are weak positive correlated, GVE and EPST, have weak negative correlation. Overall LCF and GRG have the strongest relationship and the relationships between the other variables are weak. Regarding the pairwise scatter plot Fig.4, illustrates pair-wise link among variables, each scatter plot represents how one variable predicts to another. This regression line is the shows the fits data points the best in terms of a linear relationship and the sign (positive/negative) of that relationship. The slope of the regression line represents indicated how one variable changes to another. Finally, the diagonal histograms, which show the distribution of each variable, illustrate that they seem be normal, bell-shaped and symmetric.

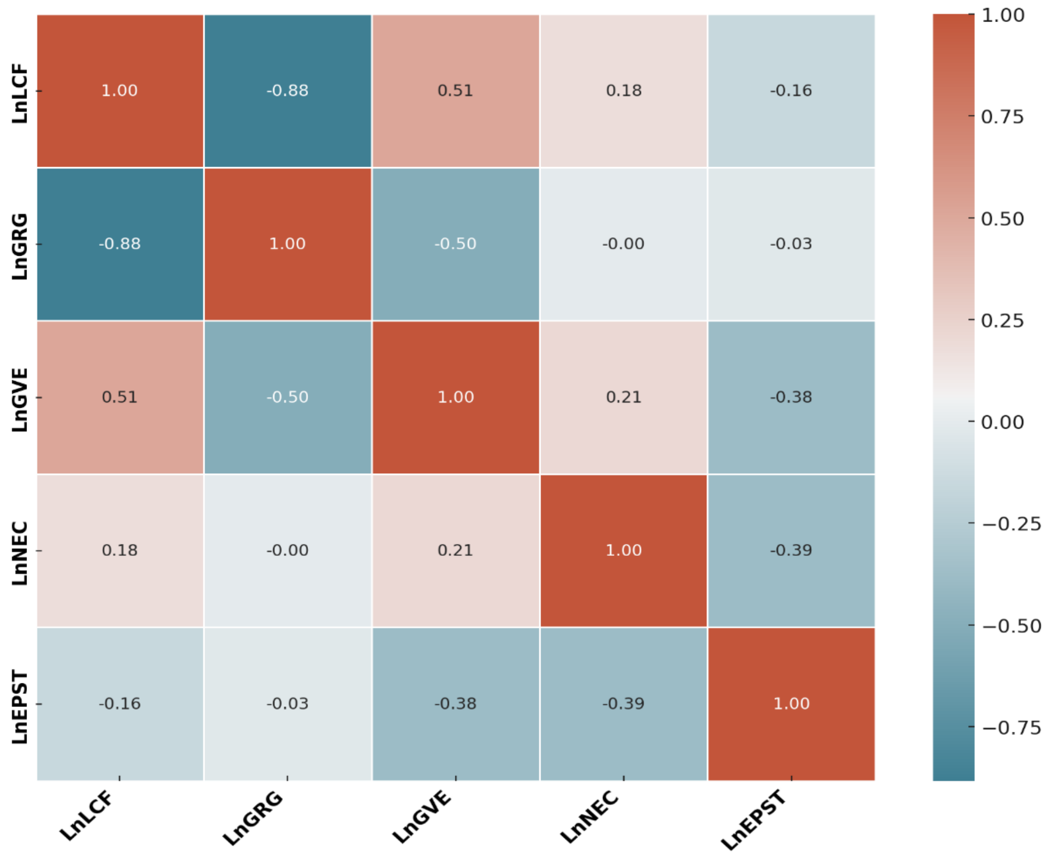

Fig.3 illustrated Correlation plot.

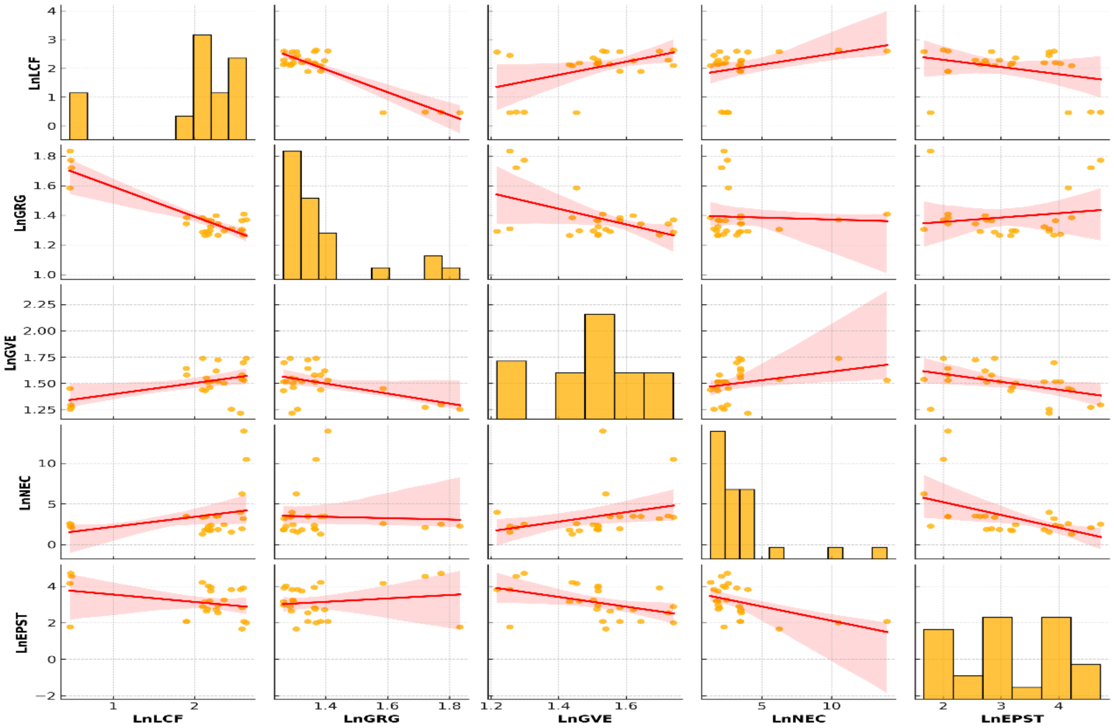

Fig.4 indicated pairwise scatter plot.

4.2. Quantile ADF and Quantile KPSS unit root tests

The Fig.5 displays the Quantile Augmented Dickey-Fuller (ADF) test statistics, used to examine the stationarity of several variables. The plot to the right of the ADF test statistics vs. each variable quantile. The three horizontal lines – dotted, dashed, and solid – reflect 0.01, 0.05 and 0.10 significance levels, respectively. The significance thresholds of the variables are compared to the test statistics at the relevant quantiles to determine the stationarity of these variables. While some variables are stationary at some quantiles, some are not. For example, the time series for the variable can be designated as stationary at 0.05 or 0.01 significance levels if the test statistic falls beyond the 0.05 or 0.01 vertical significance lines. On the other hand, if the test statistic falls between the 0.10 and 0.05 significance lines, then the variable is not stationary at the 0.10 level but is stationary at the 0.05 level. Overall, the result shown in the graph illustrates that almost all variables are stationary at 0.05 significance level, as such the price series are seasonally stationary at this level.

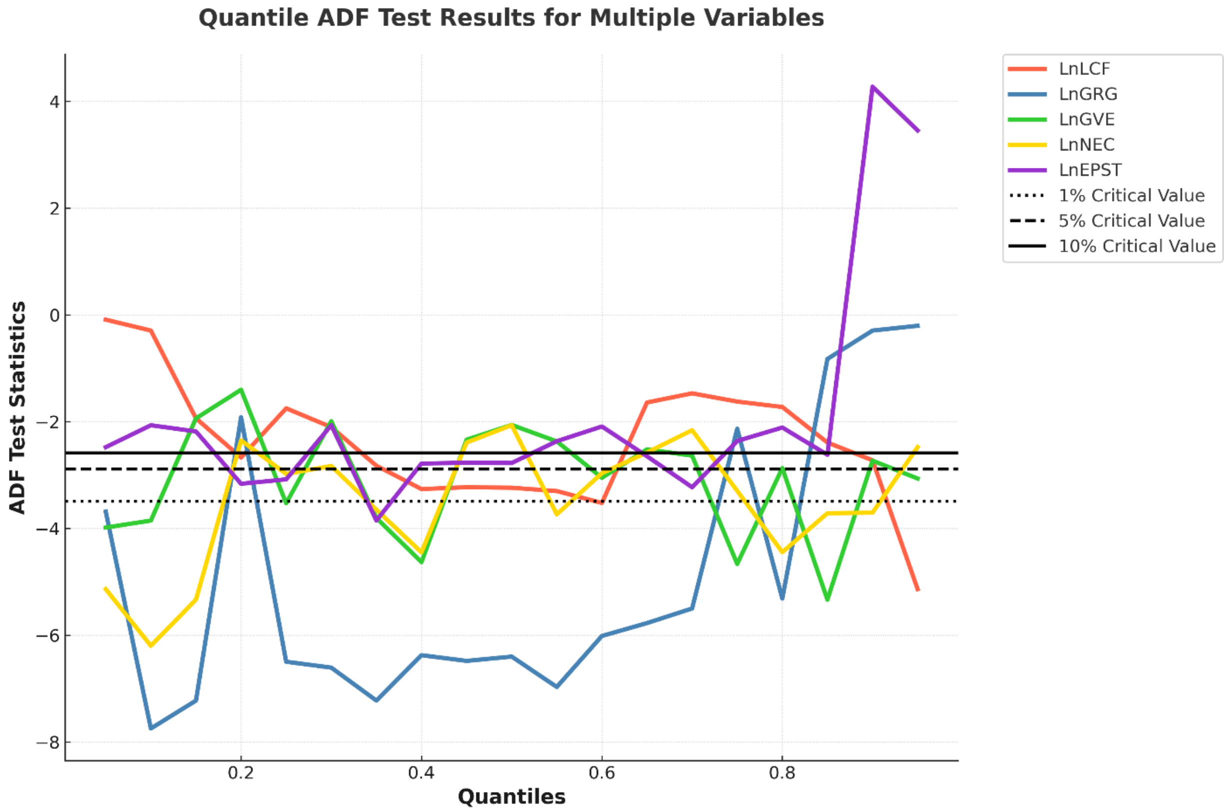

Fig.5 illustrated the quantile ADF Unit root test

The Fig.6 demonstrate the Quantile KPSS test checks whether a time series is stationary by comparing the test statistics to critical value lines corresponding to 10%, 5%, and 1% significance levels) are displayed in the graph. If the test statistic exceeds these critical values, it indicates, the variable is non stationary at that quantile. The findings point out that except for few variables, the KPSS test statistics are below the critical value lines especially at low quantiles which would imply that the variables are stationary. Specifically, both GVE and LCF demonstrate stationarity for nearly all quantiles. Although EPST and NEC show some fluctuations, their test statistics remain under the 5% threshold, proving they are stationary in most quantiles. Generally, the data is stationary as per the graph and performed well on the stationarity test across different quantiles.

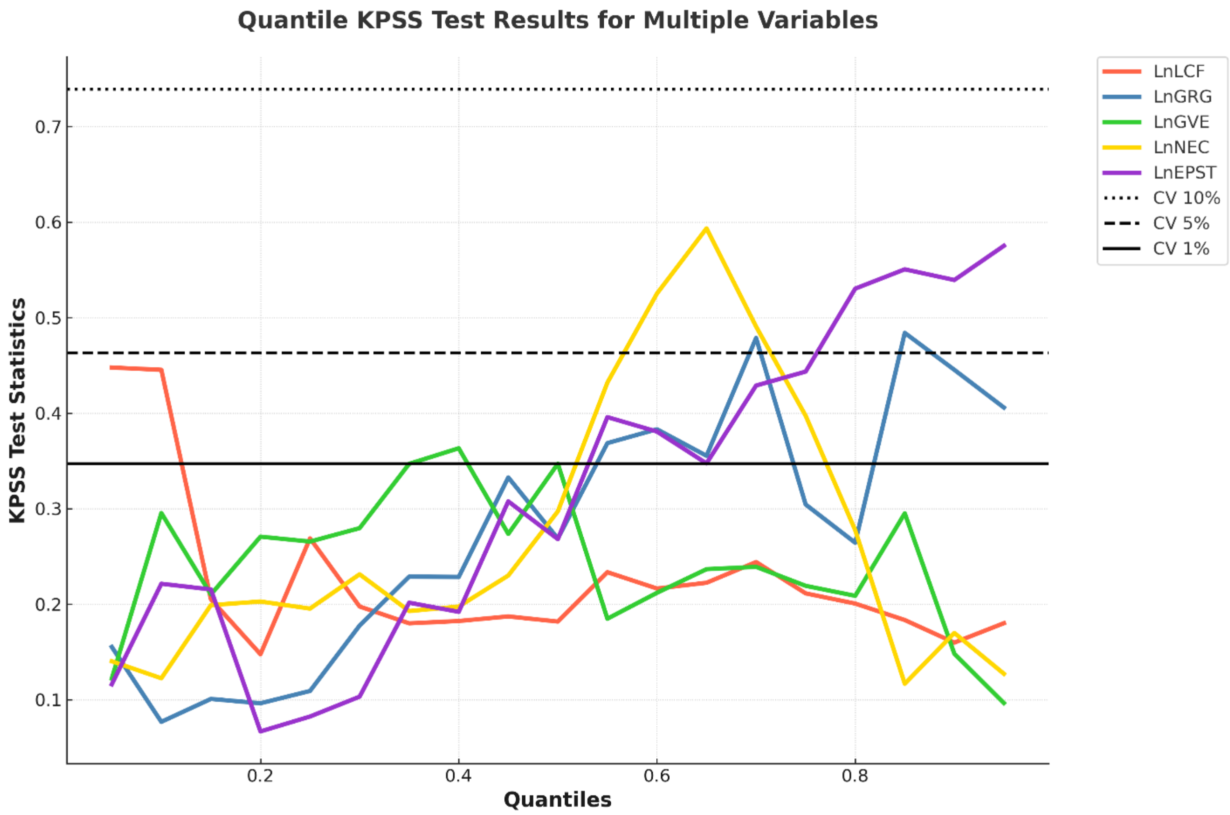

Fig.6 illustrated the quantile ADF Unit root test

4.3. Key Insights from the Multivariate QQR Analysis

In Fig. 7(a), the three dimension surface shows the impact of the Load Capacity Factor (LCF) on Green Growth (represented quantiles of the LnGRG variable) and shows the meaningful patterns and differences in this relationship. The plot shows some degree of asymmetry in this relationship, indicating that the interaction between LCF and green growth can potentially be positive, negative, or neutral depending on the quantile values of both variables. From the deep assessment of the model, it can be viewed that for the upper quantiles (0.6 to 0.8), there is a greatly positive correlation of the Green Growth (LnGRG) with the Load Capacity Factor (LCF). This means that for these quantiles at least green growth is associated with a higher load capacity factor in the US, which we interpret as resulting from the use of clean energy sources and greener technologies. This means that higher investments in terms of green growth lead to energy production with higher efficiency in LCF, thus higher LCF values. Findings raise the importance of green growth strategies to improve the performance of energy systems as the USA continues to move into renewable energy transition. In addition, the map demonstrates that there are areas where the association is neutral or weaker, especially when both the Green Growth (LnGRG) and LCF are contained in the lowest quantiles or median. This may indicate, in these scenarios, that green growth initiatives in the U.S. are not wholly converting to increased energy efficiency, or increased load capacity, on the grid. Ans: This could be for reasons such as transitional barriers, policy misalignment between regions or nascent renewable energy infrastructure in a few regions. These findings can be understood as part of a wider narrative around the U.S.'s energy policy, in which green growth has largely been incentivized through the deployment of renewables, energy efficient technologies, and federal policy levers. But, while wind, solar, and nuclear power have made notable strides, energy efficiency improvements have not always been uniform across the country. Differences in regional capacity for green growth will also factor into how well green growth strategies are working locally due to availability of renewable resources, infrastructure, and local policies. Furthermore, the findings' importance is corroborated by prior research showing positive associations (Zhao et al., 2023) and (Andersen, 2024). Nonetheless, the U.S. relationship may not be the same compared to other countries with unique challenges, including political factors, technology maturity and grid capacity limits. The findings of this study can be beneficial in informing future policies in the energy transition, especially those that would aim at the decoupling of conventional energy sources. This in turn will improve the energy infrastructure of the United States of America by focusing on green growth; building more on renewable energy and encouraging greater integration of the same. Future studies may also investigate the temporal dynamics of this relationship and analyze whether government effectiveness and energy policy stringency may impact this result at a specific point in time.

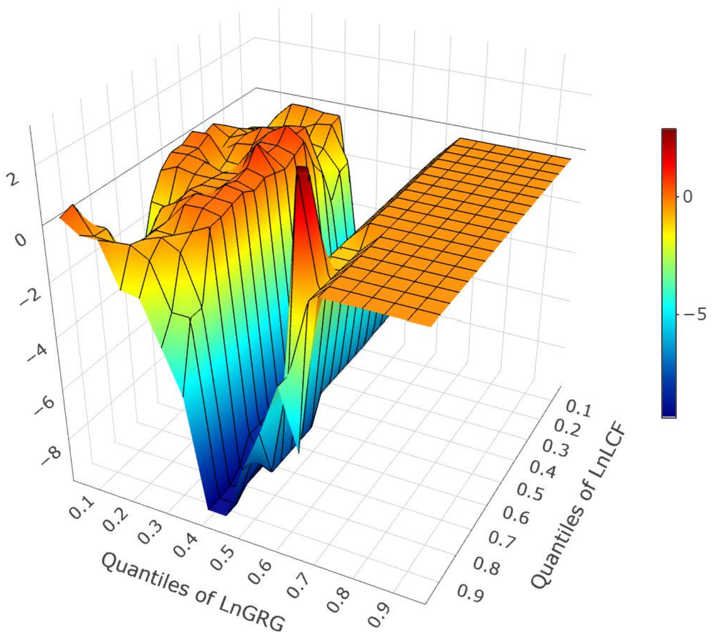

Fig.7(a) quantiles of LnLCF=f(LnGRG)

In Fig. 7(b) which, in the 3D surface, shows a negative association of government effectiveness (LnGVE) with load capacity factor (LnLCF). Specifically, it can be seen that lower values of government effectiveness (in the lower quantiles of the LnGVE variable), the load capacity factor also tends to decrease (the color becomes darker from yellow to blue). Implying that to the extent that the government fails to promote effective policy implementation, energy infrastructure management, and energy transition management, the efficiency of the energy systems reflected by the LCF deteriorates importantly. The undesirable relationship becomes especially clear when the government effectiveness parameter is concentrated in the lower quantiles (0.2 to 0.4). Here, the failure of the government to create a proper regulatory framework, incentives, and oversight for renewable energy projects and grid management creates inefficiencies in the energy System. Consequently, less energy is produced and the grid's potential is underutilized, as evidenced by decreasing LCF values. Weak policy execution, ineffective planning, and insufficient investment in infrastructure may be major culprits behind this inefficiency. This pattern is in line with studies which claim poor governance impedes energy system optimization. Strong government effectiveness means strong compliance with energy policies, coordination of federal and state policies, and sufficient financial support for renewable energy projects. Finally, without clear and effective leadership and direction, energy systems may stagnate or underperform, delaying the transition to renewable sources. The findings of this study highlight that the effectiveness of governance is a key factor in the performance of energy systems. Without consequential government action, the U.S. will not be able to fully realize optimal energy grid capability so that it achieves the highest possible energy efficiency and load capacity factors, similar findings were obtain from (Feng et al., 2024b) and (Oyewo et al., 2024). This conclusion highlights the obstacles method for policy, institutional support and a coherent governance of energy from national and regional approaches. In conclusion, one of the take-aways from these findings is that, with few exceptions, the U.S. will continue to face challenges long-term in its attempts to bolster its energy infrastructure should effectiveness be lacking on the governing body. This will only lead to unnecessary inefficiencies and less than optimal energy resource utility. Hence, strengthening governance might, thus, be critical in such a way that the potential of clean energy systems is achieved completely and their load capacity factor is maximized over time.

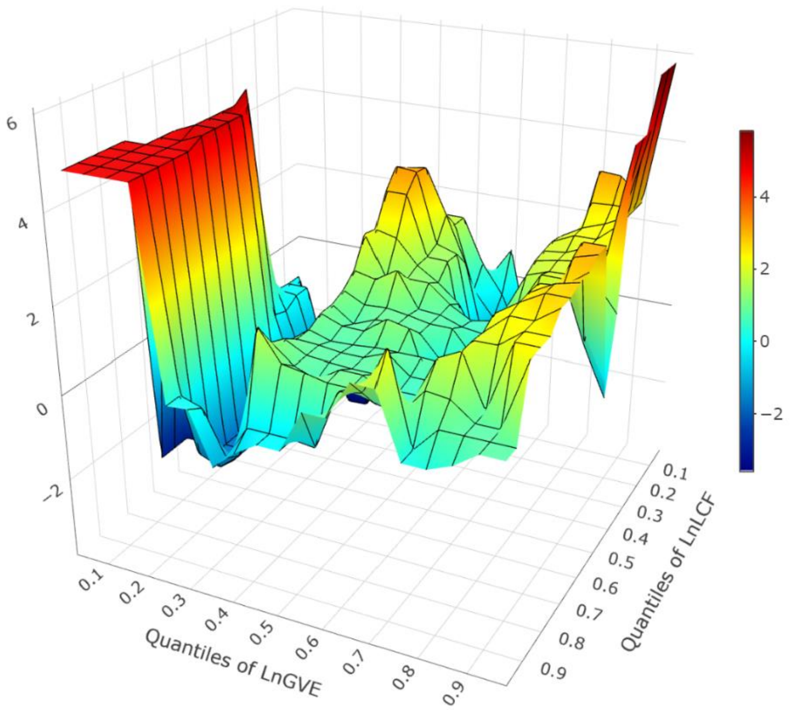

Fig.7(b) quantiles of LnLCF=f(LnGVE)

In Fig.7(c) Input data were available until October 2023. Figure5c, differential three-dimensional surface plot indicates the positive association between nuclear power consumption (LnNEC) and load capacity factor (LnLCF) (in the USA). The plot illustrates the significant contribution of nuclear energy consumption in improving the performance/efficiency of energy systems in diversified energy mix. On the other hand, In the plot, by moving to a higher quantile (0.6 to 0.8) of nuclear energy consumption (LnNEC) there is a significant increase in the load capacity factor (LnLCF), shown by using colors from cooler to warmer (blue to red). This means that nuclear energy used in the U.S. actually increases efficiency in the energy grid, courtesy of the higher load capacity factor. Nuclear supports overall grid reliability and enables the integration of intermittent renewable resources like wind and solar because of its firm, baseload generation. The high positive values in the plot also indicate that nuclear energy use is especially effective at high energy generation levels, where nuclear power plants can mediate baseload to the grid at a capacity factor optimized relative to load. This is in line with the contribution of nuclear power to reducing energy volatility and strengthening the total capacity of the U.S. energy grid. In addition, the positive association between energy system performance and nuclear energy consumption also prevails in middle and higher quantiles of nuclear energy consumption, as shown by the plot, thus affirming the importance of nuclear energy promotion in achieving a balanced energy mix and improving energy system performance. The results indicate that the load capacity factor could be improved, possibly resulting in a peaking of theU.S nuclear capacity for some time, as the country continues to develop and incorporate advanced nuclear technologies. These findings correspond well with previous literature that emphasizes how nuclear energy can contribute to both grid stability and energy efficiency (e.g., (EIA, 2022). This is essential for energy security and long-term sustainability goals, since nuclear energy is a low-carbon, stable source of energy, similar results reported (M. Ali et al., 2025; Hakkak et al., 2023; Teng et al., 2024b).

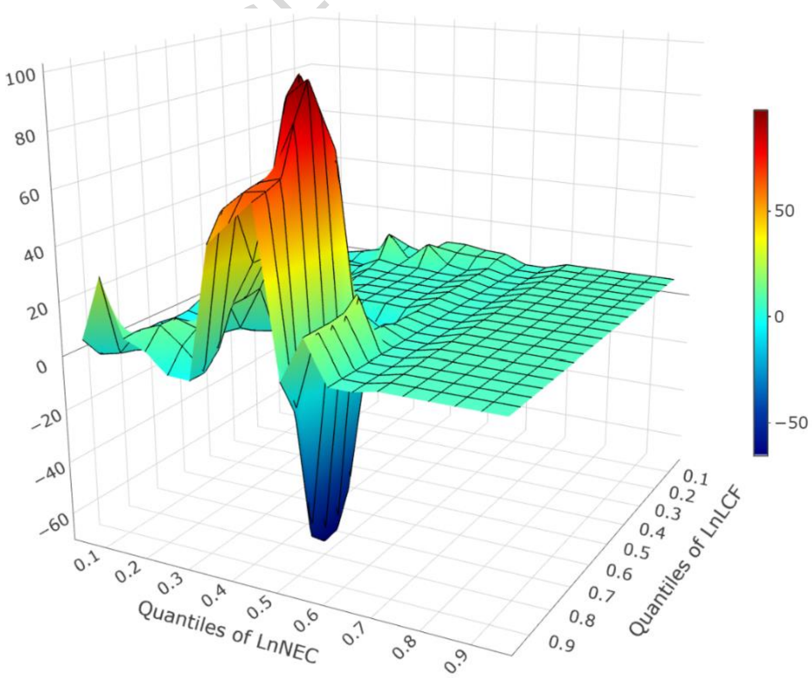

Fig.7(c) quantiles of LnLCF=f(LnNEC)

In Fig. 7(d) surface plot, three-dimensional representation of the interaction of LnEPST and LnLCF in reproducing a policy-dependent pattern in load capacity factor across the United States. There is high variability, as seen in the peaks and troughs in different quantiles of the two vars, with these being interrelated, meaning that the effectiveness of environmental policies on energy performance can evolve potentially in quite dynamic ways; At the higher quantiles of environmental policy stringency (LnEPST ~ 0.6 to 0.8), however, the load capacity factor (LnLCF) appears to increase, as indicated by the warmer colors (yellow and red). This suggests that more rigorous environmental policies are correlated with increased energy efficiency and performance. More precisely, within these quantiles, stronger environmental policies lead to improved energy management, facilitate the progressive adoption of cleaner technologies, and promote integrating renewable energy sources into the grid more efficiently, all of which contribute to a higher load capacity factor. These findings support the idea that environmental regulations have positive effects on grid performance by stimulating efficiency and renewable investment in operation. However, we find that at lower quantiles of environmental policy stringency (10–40%), the relationship reverses, as displayed by the lower load capacity factor (Indicated by cooler color, blue, green), the findings are line with (Huang et al., 2024) and (Sohag et al., 2024). As a result, weak environmental policies could negatively impact performance of the energy system, with less-stringent desiring regulations potentially leading to poor-quality energy practices, sluggish adoption of cleaner technologies and inadequate infrastructure. When environmental policy stringency of a region is low, energy systems will find it unsupported for optimization and therefore, load capacity factors will be lower. The observed variation in this relationship between environmental policy stringency and load capacity factor might also capture immediate impacts of policy changes over the current week. For instance, recent or newly enacted policies may have a longer period before they are fully realized or recognized in the energy grid. As such, the immediate impacts of such policies may be muted, especially in the first few years the policies are in place, before longer-term benefits manifest. The short-term and long-term effects of policies on energy efficiency highlight the temporal nature of these impacts. Finally, our finding of the impact of environmental policy effectiveness on energy system performance is supported by recent studies, which indicate the need for strong and comprehensive policy frameworks for sustainability, system optimization and renewables integration over the long term IEA (IEA, 2022.). While much work remains on the U.S. environmental policy agenda moving forward, developing policy stringency could be critical to accelerate the shift towards a more sustainable and functional energy system.

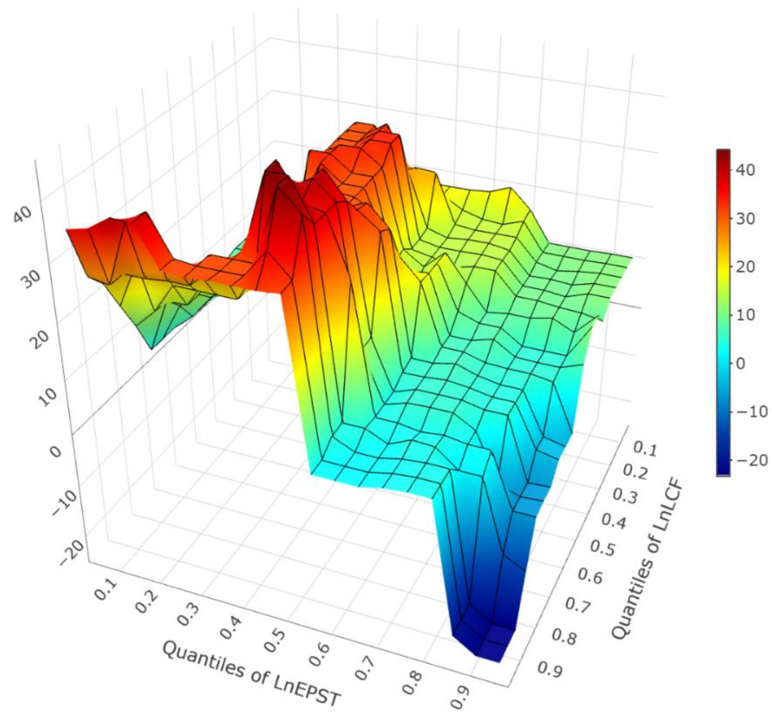

Fig.7(d) quantiles of LnLCF=f(LnEPST)

4.4. Quantile-on-Quantile Granger Causality (QQGC)

Fig.8(a) illustrates the relationship between GRE and LCF. These eco-friendly practices help to urge sustainable and efficient energy development. If the association is not as strong as that of NEC or EPST, some quantiles of the results shows that even indirectly, green growth initiative can lead to an increased load capacity factor through a renewed effort in m&e of the energy technologies both at micro and macro level. Green growth strategies can drive the energy sector to higher efficiency at specific quantiles, mainly in regions with high investment in renewables or clean technologies. Second, Fig.8(b) confirms that the GVE aspect of LCF. Here, we note the causality to be relatively weak, which does suggest that the aforementioned government effectiveness may play a role in getting energy resources managed or allocated efficiently, but the immediate causality to load capacity factor is relatively weak compared to those of Nuclear Energy or Environmental Policy Stringency. While LCF may not directly correlate with government effectiveness, an effective government can ensure that energy policies and investments are implemented effectively, thus improving LCF indirectly. Third, Fig.8(c), which describes the prediciton between NEC variable and the LCF. Causality stronger (marked by the darker shades and asterisks) suggests that the quantity of energy (in this case generated from nuclear sources) has a significant effect on LCF at particular quantiles. Significant results at some quantiles, as an example at (0.35 and 0.45), imply that, to a large extent, nuclear energy infrastructure contributes to the effective generation of energy, particularly in provinces where energy production seems to be limited or in which nuclear power is an important segment of the structure of energy. Finally, Fig.8(d) suggests tht the significant causal relation at higher quantiles, e.g. 0.75, reflects the idea that stringent environmental policy favours the energy efficiency of generation. This is due to stringent policies that promote adopting. more efficient, low carbon technologies, thereby increasing load capacity factor. The policies may also incentivize energy producers to invest in infrastructure and technologies that optimize the energy production capacity.

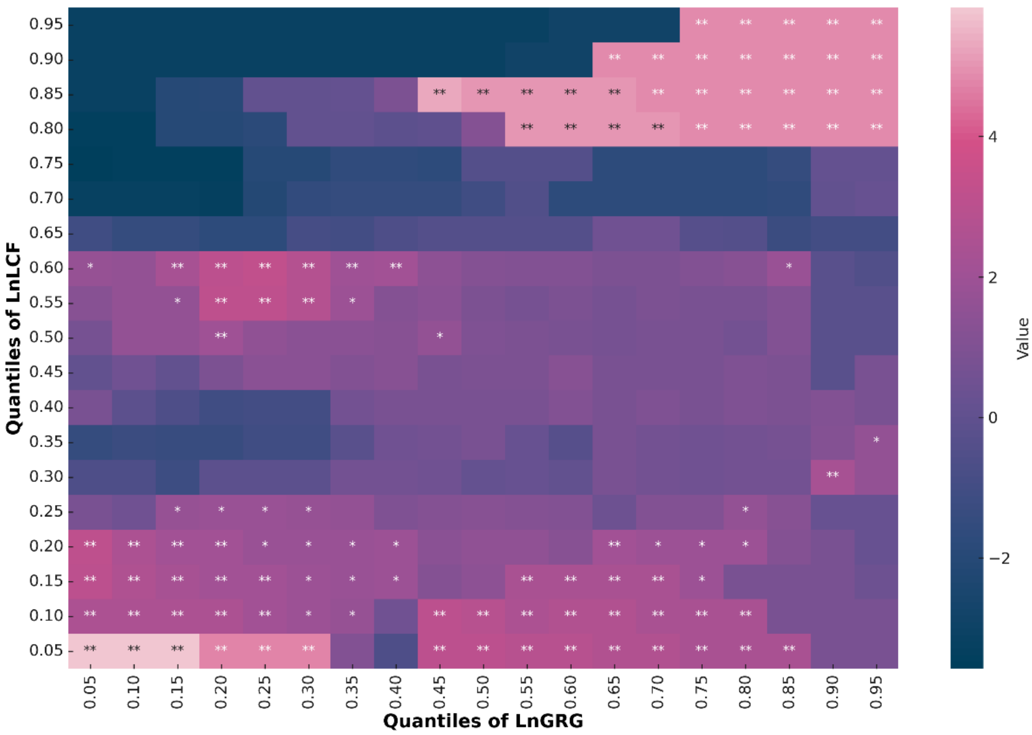

Fig.8(a) Quantile-on-quantile Granger causality

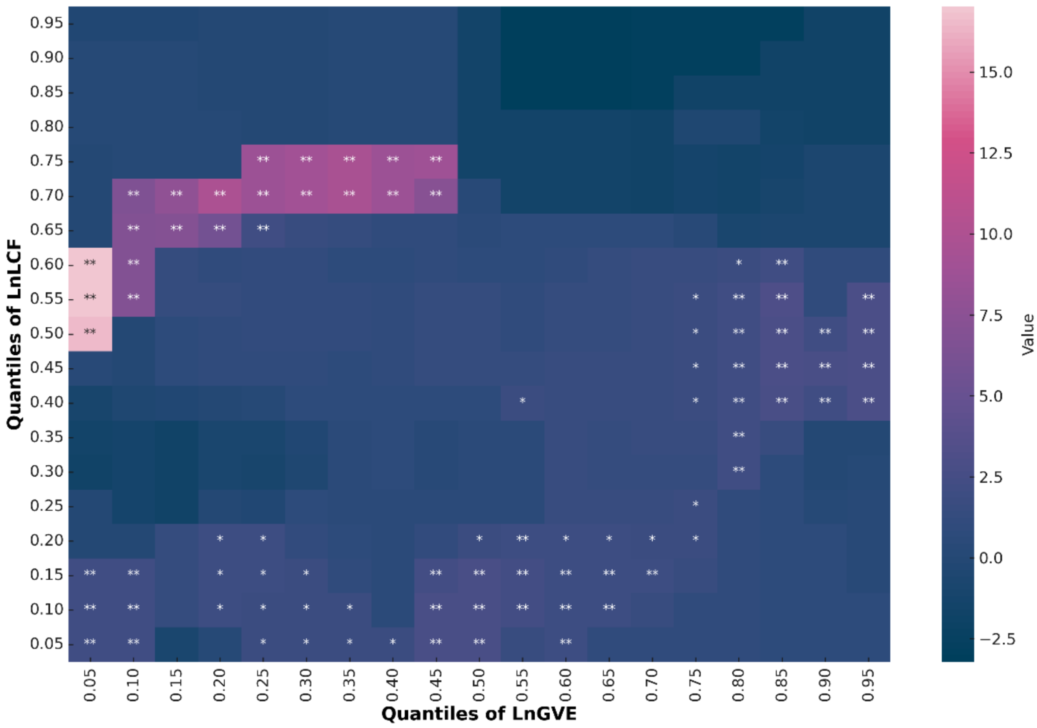

Fig.8(b) Quantile-on-quantile Granger causality

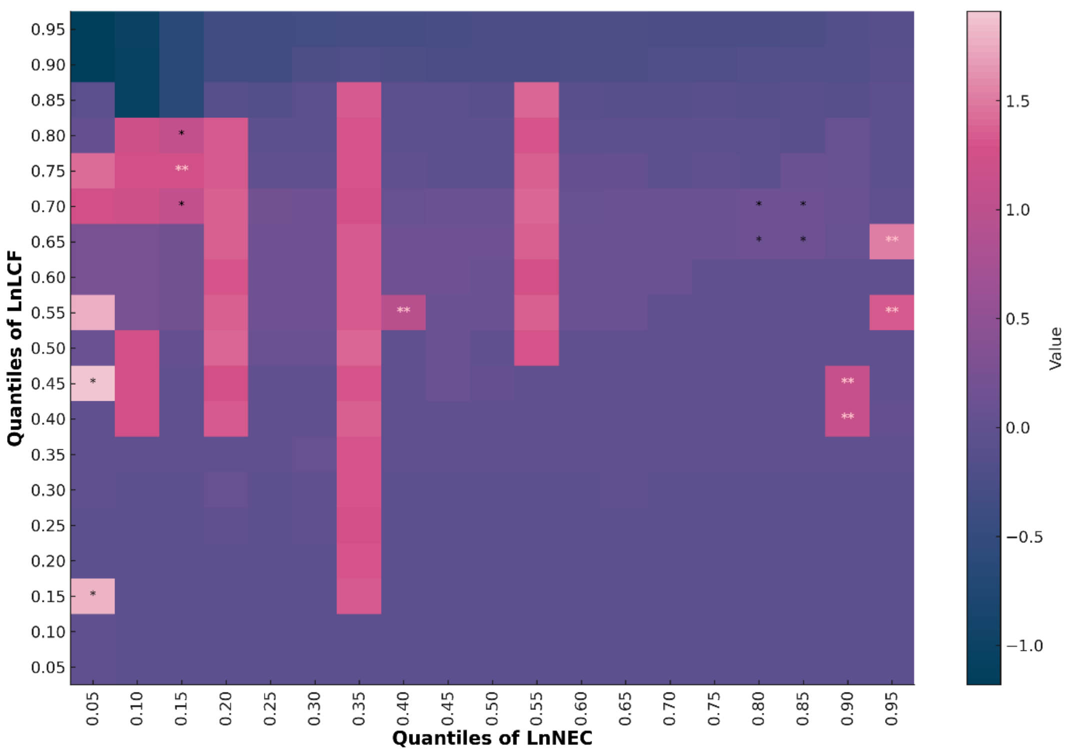

Fig.8(c) Quantile-on-quantile Granger causality

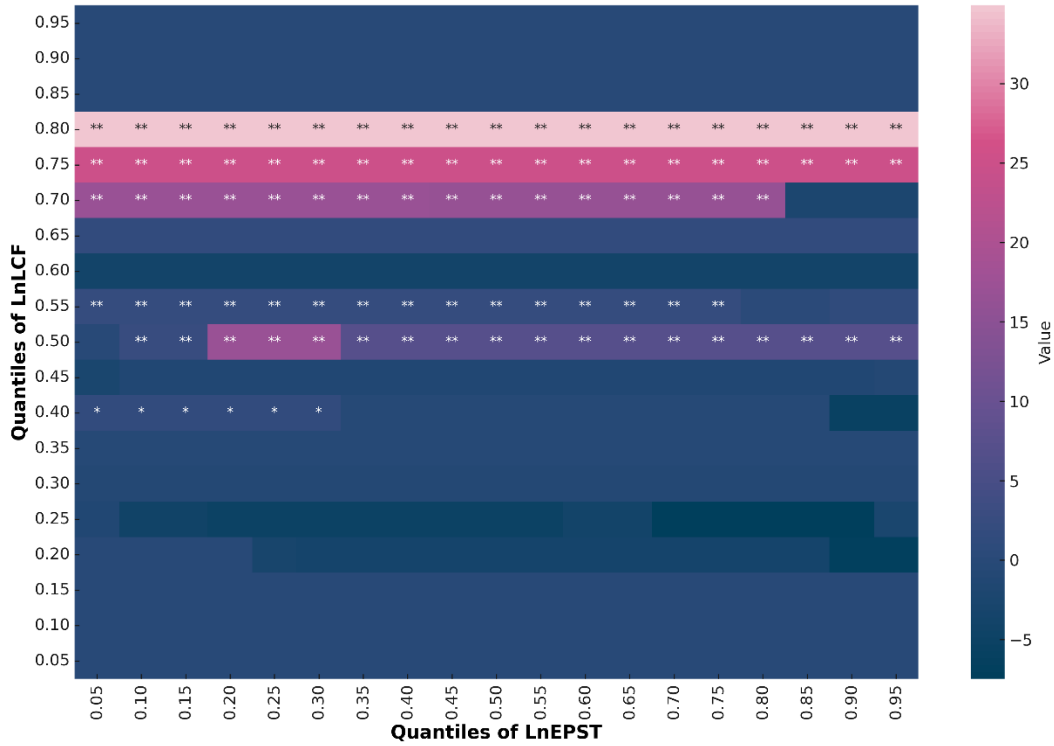

Fig.8(d) Quantile-on-quantile Granger causality

5. Conclusion and Policy implications

In this research we analyses the impact of Load Capacity Factor (LCF), Green Growth (GRG), Nuclear Energy (NEC), Government Effectiveness (GVE) and Environmental Policy Stringency (EPST) on the energy efficiency and access in the United States. We control at each level for key economic and policy factors to ensure robust estimates. The two have major socio-economic implications, making energy efficiency and access a vital area of research. Inefficiencies continue to affect both developing and developed nations like the USA energy systems, implicitly altering the lifestyles of the public and making it possible in several cases to compromise on socio-economic growth to improve environmental sustainability. Using annual data from 1973–2023, we analyze the asymmetric linkages of LCF with its determinants. (We first start with Multivariate Quantile-on-Quantile Regression, which is a regression adjustment technique to account for the fact that the data may not be linear, M-QQR.) Similar to the standard regression, but this method allows us to capture the heterogeneous relationship between LCF and the explanatory variables at the different quantiles. M-QQR offers robust estimates while accounting for time-varying effects and nonlinearities in the dataset by controlling for numerous covariates. Then, we also conduct the Quantile-on-Quantile Granger Causality (QQGC) test as another robustness test. QQGC test tests whether or not the causal relationship holds between LCF and its explanatory variables in specific quantiles of their distributions. As such, this test is especially powerful since it gives us a better picture of how causality behaves at various points of the data distribution and makes sure our results are not only based on linear assumptions. The results of QQGC test reveal the heterogeneous causal effects of GRG, NEC, GVE and EPST on LCF, providing a more in-depth analysis of the relationship between them.

5.1. Policy Implications

- ***Developing Green Growth Policies***: Energy efficiency is enhanced through green growth policies, but effect of green growth policies is not homogenous across regions. Thereby, policies focusing on stimulating green growth need to be tailored to regional circumstances and the context, including local energy infrastructure and regulatory landscapes. Focused investments in renewable energy technology, energy storage, and energy efficiency will put the nation on a path to sustainable green growth.
- ***Advancing Development of Nuclear Energy***: Due to the important contribution nuclear power makes in increasing the Load Capacity Factor and transition to low carbon energy mix, the policy issues related to regulatory and social acceptance of nuclear power will need to be addressed by policy makers. For nuclear to be used to its full potential, there will need to be an investment in new nuclear technology, including Small Modular

Reactors (SMRs), and a clear message will need to have been communicated about safety and the benefits for the environment.

- ***Enhancing the Level of Governance and Policy Coordination***: The results indicate government effectiveness to be an essential condition for energy system enhancement and energy efficiency advancement. Policy-makers should concentrate on bolstering institutional frameworks, and on better implementation of energy policies to back up energy infrastructure and to ensure optimal integration of national grid is facilitated by the renewable energy development initiatives. Good governance can clout these inefficiencies and encourage take-up of cleaner, more efficient technology.
- ***Robust environmental policies*****:** The contribution of strict environmental policy to promoting energy efficiency has been emphasized in the work. Policymakers should look to reinforce regulations that encourage investment in renewables, energy storage and grid modernisation. Also, there is the fact that policies that are conducive to enhancements in energy in-efficiencies as well as fossil fuel dependency are absolutely necessary to achieve the goals of (1) security of energy and (2) environmental sustainability.
- ***Long Run Monitoring and Adaptation***: Results of this study suggest that policy intervention impacts, at least in terms of environmental stringency, may not be immediately observed. Thus, energy transition and effects of the new policies to energy efficiency and carbon emission need to be continuously monitored. Policymakers should implement evolutionary policies to maintain energy systems resilient to new challenges, e.g., climate change and rapid changes in energy demands.

5.2. Limitation and Future direction

The study has a number of limitations due to data availability, such as regional data availability for energy infrastructures and actual long-term data quality, and the robustness of conclusions might be affected, especially for areas where energy transitions have just started or are not well-distributed. In addition, this work is limited to the U.S., with findings not necessarily applicable in other countries with different energy mixes, governance systems or policy environments. The analysis does not consider short-term dynamics that may change the early effects (at least for the next few years) of policy changes on energy systems, and is primarily based on quantitative techniques, which might be unable to capture qualitative aspects such as public acceptance and political trust. Future studies could overcome such limitations by examining differences by region in the U.S., including social and behavior factors in energy policy analysis, and examining short-term effects of energy policy. Moreover, there might be need to expand the scope of analysis across nations/regions for comparative analyses, as well as to explore timely technologies, including advanced nuclear reactor technology and energy storage, to better understand the global clean energy transition and its sustainability impacts.

Declarations

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

Ethics and consent to participate declarations
Not applicable

Consent to publish
All authors have given consent to the publication of this article.

Competing interests
The authors declare no competing interests.

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