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Energy efficiency and environmental degradation nexus: evidence from the Quantile-on-Quantile regression technique

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ABSTRACT

The world is facing enormous challenge of climate change and global warming due to increased emission level. In order to overcome such challenges, economies are adopting energy efficient techniques to control the carbon emissions and improves environmental sustainability. This study analyses the influencing factors of environmental quality from a global perspective throughout the last three decades. In this regard, advanced time series approaches are used to identify the association between factors such as economic growth, energy efficiency (E.N.E.F.), and carbon emissions – covering global data over the period 1990Q_4–2020Q_4. From the time series methods, this study observed the stationarity of all variables at first difference. The empirical outcomes also validates the long-run equilibrium relationship between the variables. Due to asymmetric distribution of the variables, this study uses the novel Quantile-on-Quantile (Q.Q.) regression approach, which reveals that increasing economic growth harms environmental quality by increasing the carbon emissions level. However, E.N.E.F. is a prominent factor of environmental sustainability, that reduces the level of carbon emissions in the atmosphere. Employing the pairwise Granger causality test, this study observed the unidirectional causality from economic growth to carbon emissions, while a two-way causal nexus is found between economic growth – E.N.E.F. and E.N.E.F. – carbon emissions. Based on the empirical results, this study suggests that economic growth should be regulated in a sense that it contribute towards the improvement of E.N.E.F., which ultimately leads to reduce the emissions level and promote environmental sustainability.

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1. Introduction

To counteract environmental deterioration, global economies have partnered on a number of initiatives, like the 'Paris Agreement on Climate Change 2015', to limit global warming to less than 2 °C. Most of the countries have established goals for carbon neutrality or zero carbon emissions. According to British Standard Institution, PAS 2060, 'carbon neutrality is a situation within a set period of time in which there are no net greenhouse gas emissions'. To achieve environmental sustainability, both industrialised and emerging economies are targeting carbon neutrality. For instance, China – the world's largest emitter of carbon dioxide, is urging cities and organisations to transition to carbon neutrality and reduce carbon emissions by 70% by 2050 (CNCA, 2019).[1] Nationally Determined Contributions are the defining characteristic of the Paris accord, in which nations establish their domestic targets for reducing carbon emissions.

Environmental sustainability refers to the security of natural assets and the environment's continuous development (Hafeez et al., 2018; Murshed et al., 2021). Agriculture and forestry are key carbon pollution generators (Hafeez et al., 2020). Consequently, as part of its strategy for environmental sustainability and green development, the United Nations has demanded that all international players affirm increased global access to safe, accessible, advanced, and clean resources of energy. In this context, Sustainable Development Goal 7 (SDG-7) emphasises energy efficiency (E.N.E.F.) and the use of renewable energy in the overall power consumption composition (Murshed et al., 2021).

The importance of energy to a nation's economic prosperity cannot be overstated, yet its biggest drawback is the global warming and climate change related issues (Murshed & Tanha, 2021). Due to a 50% increase in energy usage over the previous couple of decades, the negative impacts of global warming are becoming considerably more apparent (Akram et al., 2020). As per Ulucak and Khan (2020), the global ecosystem is threatened by the excessive energy usage. Increasing population, a rapid economic growth rate, extensive industrialisation, and increased mobility and infrastructure are the primary causes of the increase in energy utilisation during the last two decades (Espa & Holzer, 2018; Ozturk & Bilgili, 2015). The energy sector is the primary contributor to global emissions, accounting for about two-thirds of all greenhouse gas emissions (Anderson et al., 2013). Since roughly 80% of the world's energy utilisation originates from traditional fossil fuels, there is a positive correlation between energy use and carbon emissions.

In both emerging and industrialised countries, economic development is crucial because it enhances the quality of life for the average individual. Therefore, authorities should strike the right balance between the task of improving environmental quality and the objective of generating rapid economic growth. As stated by the World Bank in 2021, the global G.D.P. has expanded from US$35.87 trillion in 1990 to US$81.9 trillion in 2020 as a result of the expansion of globalisation and international trade.[2] However, such an advancement in global economic conditions has seriously compromised environmental quality in most regions and increase carbon emissions, with both industrialised (such as the United States) and emerging (such as China) economies contributing to global environmental degradation as the leading carbon emitters. The global trend of growing carbon emissions is a cause for concern not just for the general public but also for global policymakers. Consequently, the environmental economist has promoted the use of renewable energy sources rather than conventional ones. On the other hand, they have also attempted to improve energy sector efficiency and advocated conservation programs to cut emissions without sacrificing economic development (de Castro Camioto et al., 2016). The quality of environmental will improve as a consequence of the growing use of environmentally friendly energy resources and the effective implementation of legislation related to E.N.E.F., which will reduce carbon emissions and boost E.N.E.F. across the globe. Nonetheless, several authors have validated the positive role of E.N.E.F. in the environmental quality improvement, for instance, in case of the European countries (Akdag & Yıldırım, 2020), and developing economies (Akram et al., 2020). Such studies motivates the study to empirically analyse the global E.N.E.F. trends and environmental quality.

The main purpose of the research is to evaluate the environmental nexus with E.N.E.F. As mentioned earlier, E.N.E.F. could lead the global environmental quality towards improvement via reducing the carbon emissions level. However, such statements requires empirical evidence, which this study evaluates via adopting novel econometric approaches. Another objective of this study is to empirically investigate the influence of economic growth on the global carbon emissions in the last three decades. Since the global economy is rapidly expanding over the past few years. Consequently, the industrial production, investment level, income level, and the consumption level surges, which boost energy demand, particularly the fossil fuels. However, the empirical evidence regarding the said nexus is limited in terms of global economy, which is important for policymakers and future researchers.

This study is novel and contributes to the existing literature in three ways. Firstly, the literature is limited in terms of identifying the nexus between E.N.E.F. and environmental quality. Although the literature mentioned several studies that explores this relationship. Unlike other studies, this study provides a broad picture of the nexus between the variables by considering the global data, which will not benefit scholars, but also be advantageous for the policymakers. Secondly, this study explores the relationship between the global economic growth and global carbon emissions, which makes this study unique as the existing literature is limited to a specific country or region. Whereas economic growth is dependent on the industrialisation and trading across countries. Therefore, it is essential to consider global economy in the empirical investigation, empirical results of which could be generalised to specific economies. Besides, climate change and environmental degradation are the global concerns, which requires global level attention. Therefore, the empirical outcomes of this research could help in the policy development that targets environmental sustainability and economic growth. Moreover, this study uses an extended time-series data, which could also consider the recent trend in the global economic growth, E.N.E.F., and carbon emissions. Thus, the empirical outcomes of this study could capture more view of the association between the variables, which is the need of the time.

The remaining manuscript is organised as follows: the next section 2 comprises a literature review of the study. Section 3 demonstrates methodology, highlights of research data, and model and approaches used. Section 4 is about the results and their brief discussions while Section 5 deals with the conclusion and policy implications related to the study.

2. Literature review

This section provides relevant literature review, covering different countries, regions, and periods regarding the association of E.N.E.F., economic growth, and carbon emissions.

The existing literature is rich in reporting the factors affecting carbon emissions in a country. For instance, energy use, urbanisation, energy intensity, manufacturing value-added, financial development, among others (Khan et al., 2021; Khan, Hou et al., 2022; Zahoor et al., 2022). However, studies such as Khan et al. (2020), Ma et al. (2021), Qin, Raheem, et al. (2021), Qin, Hou, et al. (2021), Shahzad et al. (2021), Khan et al. (2019) and Hasanov et al. (2021) claimed that eco-innovation, technological innovation, renewable energy, renewable electricity, environmental regulations, among others are the remedial measure of environmental degradation. On the other hand, the literature is also extensive regarding the consideration of E.N.E.F. as a tool for environmental sustainability. The Institute of Environment and Energy study defined E.N.E.F. as performing the same level of tasks via less amount of energy that will help in limiting the carbon and greenhouse emissions and their costs at the national and international level (EESI, 2022). The strategy of E.N.E.F. could be acquired via the use of renewable energy resources. Since the last few decades, E.N.E.F. is regarded as an optimal tool for environmental recovery, emissions reduction, and tackling global warming (Endo, 1993). The recent study of Akram et al. (2022) examined the asymmetric influence of renewable energy and E.N.E.F. on carbon dioxide emissions in M.I.N.T. economies. this study is considered as the first attempt to explores the mitigating effects of E.N.E.F. on greenhouse emissions in 'Mexico, Indonesia, Nigeria, and Turkey' throughout 1990–2014. The study found that a positive shock in E.N.E.F. reduces the carbon emission(s) in both the long and short-run. Özbuğday and Erbas (2015) examined the relationship between E.N.E.F. and carbon dioxide emissions, and revealed that there exist a long-run relationship between the variables. They also concluded increasing the efficiency of energy reduces carbon dioxide emissions for 36 countries during 1971–2009. Since technology and energy varies across the regions, that depends upon the economic growth, Therefore, the higher level of economic growth leads to higher level of E.N.E.F. (Sohag et al., 2021). In addition, Razzaq et al. (2021) inspected the inverse association between efficient energy and carbon emissions. The study concludes that enhancement in E.N.E.F. could substantially reduce the carbon emissions level, which is also playing a positive role in improving the economic growth of the region, which is also validated by the recent study of Khan, Zakari, et al. (2022). On the other hand, Mahapatra and Irfan (2021) found diverse influences but the irregular impact of E.N.E.F. and carbon emissions. The study validate inconsistent impact of E.N.E.F. on environmental quality. Another recent study of Ponce and Khan (2021) analysed the role of E.N.E.F. in developed economies' carbon emissions throughout 1995–2019. The estimated results of the study found a negative correlation between E.N.E.F. and carbon dioxide emissions in the region. In the case of China, Li and Colombier (2009) argued that enhancing E.N.E.F. building could mitigates the climate reduction credits and manages emissions in the country. Furthermore, there are several studies that empirically analysed the nexus of E.N.E.F. and carbon emissions (Akbar et al., 2021; Akram et al., 2020; Hassan et al., 2022; Mirza et al., 2022; Muhammad & Saad, 2018; Pardo Martínez & Silveira, 2013). These studies have empirically studied the association between E.N.E.F. and carbon emissions in various economies while adopting different time periods. Using several econometric approaches, these studies validates the negative influence of E.N.E.F. on carbon emissions. Besides, the studies argued that increasing E.N.E.F. generally requires an initial investment, but in the majority of situations, such expenses are quickly recovered via lower energy costs. This makes increases in efficiency an ideal starting point for decreasing carbon emissions.

Concerning the nexus of economic growth carbon emissions, the literature is extensive. For instance, Antonakakis et al. (2017) analysed 106 countries over the period 1971–2011 and observed that increasing growth levels in the country increases carbon emissions. The recent study of Shikwambana et al. (2021) examined the association between economic growth and carbon emissions in South Africa during 1994–2019. Using various econometric approaches, the study found that there exists an increasing trend between emissions and economic growth in the country throughout 1994–2016. This indicates a positive association between economic expansion and environmental degradation. In addition, Fei et al. (2011) investigated 30 provinces of China over the period from 1985 to 2007. The examined results demonstrated that increase in Gross domestic product per capita led to an increase the energy consumption and consequently increases carbon emissions in the provinces of China. Similarly, Chen et al. (2022) analysed economic growth and carbon emissions along with several control variables in B.R.I.C. countries between 1990 and 2019. Using novel panel econometric approaches, the study illustrates bi-directional causality between the research variables economic growth and environmental degradation. The study also found that economic growth or G.D.P. is a substantial determining factor of the emissions during the said period. One of the recent study of Shabani et al. (2022) investigated the association of economic growth and carbon emissions in O.E.C.D. member economies from 1990 to 2014. The empirical findings of the study claimed that economic growth exhibit positive and statistically significant influence of economic growth on greenhouse emissions. The authors further argued that utilising solar energy and other efficient methods helps in mitigating climate change and emissions related issues, particularly by reducing ecological footprint (Sharif et al., 2021). Additionally, Mohsin et al. (2022) confirmed the long-run and short-run associations of economic growth and carbon emissions in Central Asia and European economies throughout 1971–2016. Using Autoregressive distributed lags model, the study found that there is a positive association in the short run, while a negative association in the long run between economic growth and carbon emissions. The authors further claimed that green resources for energy help in maintaining environmental sustainability. In case of the United States, Salari et al. (2021) also inspected the association of economic growth, carbon emissions, and energy consumption over the period

1977–2016. The study validates the Environmental Kuznets hypothesis, i.e., there is a momentous association between G.D.P. and carbon dioxide emissions. The study also employed robustness tools for validity and reliability of the results in dynamic and static models. In the case of Nigeria, Olayungbo et al. (2022) confirmed the environmental Kuznets hypothesis displaying an inverted U-shaped association between the variables between economic growth and environmental quality. Specifically, the findings asserted that in the initial stages of development, the economic growth increases carbon emissions. But after achieving the threshold level of incomes, the economy tends to use environmentally friendly resources, which promotes environmental sustainability. During the period from 1990 to 2014, Nathaniel et al. (2021) observed inter-associations of carbon emissions and economic growth in African economies. The outcomes have no contemporaneous influence on emissions but then again there is a negative effect at a single period lag over the growth of the economy. Moreover, the study of Khan, Tan, and Hassan (2022) and Khan, Tan, Azam, et al. (2022) demonstrates that higher economic growth leads to the adoption of nuclear and alternate energy sources, which leads to reduce the carbon emissions level and ecological footprint.

3. Data and Methodology

3.1. Data and Variables' Specification

To identify the influencing factors of environmental quality, this study undertakes the carbon (CO_2: measured in kt) emissions as a proxy of environmental degradation. Since the CO_2 emissions is regarded the most emitting gas in greenhouse gas emissions. Therefore, most of the scholars asserted that using CO_2 emissions as an environmental quality indicator is an appropriate measure (Fei et al., 2011; Mohsin et al., 2022). Nonetheless, every economic activity is connected to economic growth of the country or region. In the recent times, economies are paying more attention towards the development of the industrial sector, and stability of G.D.P., which is an important indicator for economy health. The G.D.P. influences CO_2 emissions in various perspective, where the most prominent is the industrial or energy consumption channel. Therefore, this study uses G.D.P. (measured in constant US$2015) as a proxy of economic growth. Concerning remedial measures for environmental sustainability, various measures have been employed. Where scholars have paid more attention towards adoption of the E.N.E.F. for attaining low carbon economy. Generally, the term E.N.E.F. refers to the G.D.P. per unit of energy use and is measured in P.P.P. $per kg of oil equivalent. Therefore, this study aims to investigate the association of global E.N.E.F. and global carbon emissions. In order to comprehensively analyse the said nexus, this study uses quarterly data obtained from the world development indicators (World Bank, 2022), that covers the period from 1990Q1 to 2020Q4.

3.2. Estimation Techniques

3.2.1. Descriptive statistics and Normality

To prepare for performing the empirical analysis, this study developed descriptive statistics for all the under-consideration variables. In summarising the data, descriptive statistics such as the mean, median, the range (minimum and maximum), and the standard deviation (which is a fundamental measure of fluctuations in a time series variable from the mean value), are used to aid in the description of the data. The Jarque and Bera (1987) normality test, which takes into consideration both skewness and excess Kurtosis, was also utilised in this research to provide a full assessment of the data's normalcy. In this test, it is assumed that time-series data is normally distributed – termed as the null hypothesis of the Jarque-Bera test. In order to compute the values of Jarque-Bera's, the following standard equation may be used:

$$JB = \frac{N}{6}\left(S^2 + \frac{(K-3)^2}{4}\right) \tag{1}$$

Where N indicates the number of observation, S denotes the skewness, and K reports the excess Kurtosis.

3.2.2. Unit Root

In econometrics and statistics, an augmented Dickey-Fuller test (A.D.F.) proposed by Dickey and Fuller (1979) examines the claim (null hypothesis) that a time series sample contains a unit root against the vice versa as an alternative hypothesis. The A.D.F. statistic employed in this research is a negative figure. The more negative it is, the more strongly the hypothesis of a unit root is rejected at certain confidence level. The A.D.F. test is identical to the Dickey-Fuller test, which is given in the regression form below:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \delta_1 \Delta y_{t-1} + \delta_2 \Delta y_{t-2} + \ldots + \delta_\rho \Delta y_{t-\rho-1} + \varepsilon_t \tag{2}$$

From Equation (2), α represents constant, β denotes coefficient on a time trend, and ρ is the autoregressive process's lag order. Implementing the restrictions, $\alpha = 0$ and $\beta = 0$ simulates a random walk. After that, the unit root test is used to compare the null hypothesis $\gamma = 0$ to the alternative, i.e., $\gamma < 0,$ as defined:

$$DF_\tau = \frac{\hat{\gamma}}{SE(\hat{\gamma})} \tag{3}$$

After evaluating the test's statistics for the said test, it may be contrasted to the Dickey-Fuller test's critical value DF_τ. In addition to the ADF unit root test, this study also employed the Phillips-Perron unit root test to evaluates if the variables possesses unit root in the time series.

3.2.3. Cointegration

The cointegration connection between variables was examined after the data were checked for the existence of a unit root or stationarity. We employed the Bayer-Hanck combined cointegration test to assess the long-run equilibrium relationship between CO2 and E.N.E.F., and CO2 and G.D.P. This test incorporates the cointegration tests of Engle and Granger (1987), Johansen (1991), Banerjee et al. (1998), and Boswijk (1994). However, when the aforementioned tests are employed simultaneously, the cointegration test's predictive validity may provide misleading results (Shahbaz et al., 2018). As a consequence, we employed Bayer and Hanck's (2009) combined cointegration test to enhance the effectiveness of cointegration analysis and eliminate questionable or confusing estimates. The test uses Fisher's F-statistics to combine all of the mentioned cointegration tests and provide clear and accurate results (Shahbaz et al., 2018). Additionally, this test requires a different sequence of integration, i.e., I (1). As a null hypothesis, it presupposes that the investigated variables are not cointegrated. This may be denied, however, if the expected statistics are significant at any level of significance, such as 10%, 5%, or 1%. The following summarises Fisher's formula for Bayer-Hanck cointegration:

$$\mathrm{EG}-J=-2\left[\ln(P_{EG})+\ \ln(P_J)\right] \tag{4}$$

$$EG-J-Ba-Bo=-2\left[\ln(P_{EG})+\ \ln(P_J)+\ln(P_{Ba})+\ln(P_{Bo})\right] \tag{5}$$

In Equation (5), the probability values for Engle and Granger (1987), Johansen's (1991), Banerjee's et al. (1998), and Boswijk's (1994) cointegration tests are P_{EG}, P_j, P_{Ba}, and P_{Bo}, respectively.

3.2.4. Quantile-on-Quantile Regression

The present research utilises Sim and Zhou (2015) Quantile-on-Quantile (Q.Q.) approach. This method, also known as generalising the conventional and standard quantile regression models – enables the quantiles of one variable to be compared to the quantiles of another variable. Additionally, it integrates two approaches: quantile regression, which examines the effect of indicators on the quantiles of a response variable, and the non-parametric approach. The more advanced version of ordinary least square (O.L.S.) regression analysis, in which the variable's average is compared to the average of another variable, was first proposed by Koenker and Bassett (1978). Quantile regression, on the other hand, may account for a bigger proportion of the variation in quantiles, enabling experts to predict more accurately. Furthermore, as argued and reported by Stone (1977) and Cleveland (1979), the classical regression decreases the dimension of the data in order to fit a linear function, resulting in a loss of prediction accuracy. On the other hand, when the quantiles of predictor factors are compared to the quantiles of a response variable, as permitted by the Q.Q. approach, the ability to forecast improves since more variance between the components is explained (Shahzad et al., 2017). The following equation represents a non-parametric Q.Q. regression model:

$$CO_{2,t}=\beta^{\theta}(X_t)+\mu_t^{\theta}, \tag{6}$$

Where Equation (6), specifies a framework in which CO_2 reflects quarterly carbon dioxide emissions during a specific time period t. Meanwhile, X_t is a vector that captures each regressor used in this investigation, namely *ENEF and GDP* across the time period chosen. Additionally, θ is the θth quantile, chosen on the basis of the normal conditional distribution, and the symbol μ_t^{θ} denotes the quantile's error term when the conditional θth is assumed to be zero. Additionally, $\beta^{\theta}(\cdot)$ denotes an undetermined expression owing to a lack of knowledge on the relationship between the specified independent and dependent variables, i.e., CO_2 and X_t.

The Q.Q. approach is dealing with the general behaviour of ideas and the correlations between several variables. In other words, any shocks in X_t, either negative or positive, will have the same influence on QCO_2. For instance, the instability in X_t may be negative or positive, and the QCO_2 can respond asymmetrically or symmetrically.

To examine the impact of $CO_2's\ \theta th$ quantile on $X's$ th quantile – denoted by X_t – Equation (6) might be used in conjunction with the X_t in a linear regression analysis. Due to the unnamed function of $\beta^{\theta}(\cdot)$, the first-order Taylor expansion function may be computed, which could be expressed as follows:

$$\beta^{\theta}(X_t) \approx \beta^{\theta}(X^{\tau}) + \beta^{\acute{\theta}}(X^{\tau})(X_t - X^{\tau}). \tag{7}$$

From the above-mentioned equation, $\beta^{\acute{\theta}}$ refers partial derivatives of $\beta^{\theta}(X_t)$ for each regressor – termed as response or marginal effect. While this effect could be analysed in a similar way as of the traditional linear regression approach. In addition, the index of parameters is doubled – as observed in Equation (7), that is, $\beta^{\theta}(X^{\tau})$ and $\beta^{\acute{\theta}}(X^{\tau})$ in terms of θ and τ. Moreover, the function X^{τ} reflects $\beta^{\acute{\theta}}(X^{\tau})$ and $\beta^{\theta}(X^{\tau})$, while X^{τ} is also a function of τ, that further explains $\beta^{\theta}(X^{\tau})$ and $\beta^{\acute{\theta}}(X^{\tau})$ are the operators of θ and τ. Where these operators can be restructured as $\beta_1(\theta,\ \tau)$ and $\beta_2(\theta,\ \tau)$, appropriately. Consequently, the transformed version of Equation (7) could be expressed as follows:

$$\beta^{\theta}(X^{\tau}) = \beta_1(\theta,\ \tau) + \beta_2(\theta,\ \tau)(X_t - X^{\tau}), \tag{8}$$

Where additional transformation of Equation (8) is given as Equation (9) below:

$$CO_{2,t} = \beta_1(\theta,\ \tau) + \beta_2(\theta,\ \tau)(X_t - X^{\tau}) + \mu_t^{\theta} \tag{9(*)}$$

The (*) in Equation (9) denotes the θth conditional quantile of CO_2 represents carbon emissions. The parameters of theses mentioned conditional quantile has two indices, β_1 and β_2, in terms of θ and τ, respectively, and it associates the θth quantile of CO_2 with the τth quantile of X. There is a possibility that the parameters of the θth quantiles of the CO_2 and the τth quantile of the X contradict in terms of values. Furthermore, no linear relationship between the two variables is expected at any point in time. Consequently, Equation (9) analyses the model's overall interconnectivity in terms of the variables' distribution-based dependency. Moreover, the predicted analogs $\widehat{X_t}$ and $\hat{X^{\tau}}$ in Equation (9) must be substituted for X_t and X^{τ}, accordingly. Thus, the coefficients β_1 and β_2, that are assigned by $b_1$and b_2, are predicted via local linear regression and can be derived by solving the following optimisation technique, given as:

$$min_{b_1,\ b_2} \sum_{i=1}^{n} \rho_{\theta}\left[CO_{2,t} - b_1 - b_2(\widehat{X_t} - \hat{X^{\tau}})\right] \times K\left(\frac{F_n(X_t) - \ \tau}{h}\right), \tag{10}$$

From the above equation, $\rho_\theta(u)$ represents the quantile loss function, which could be expressed as $\rho_\theta(u) = u(\theta - I\ (u > 0))$. Specifically, I represent the function of unusual indicator, while the K(*) represents kernel function, and h captures the parameters of kernel bandwidth.

In this research, the Gaussian kernel is used to estimate the weightage of the neighbourhood data of X^τ. The Gaussian kernel is a widely used, discussed, and recognised kernel function, particularly in the fields of economics and finance, since it is easy to use and evaluate. This kernel function has an advantage of being symmetric as it approaches zero, with subsequent data assigned low weights. The weighting and distances between the distribution function of $\widehat{X_t}$ are negatively associated in the current research study and are designated by $F_n(\widehat{X_t}) = \frac{1}{n}\sum_{k=1}^{n} I(\widehat{X_k} > \widehat{X_t})$, where the outcome of the distribution function may interact with the quantile $\hat{X^\tau}$ as denoted by τ.

3.2.5. Causality

Using the Q.Q. regression technique, we were able to determine the long-run relationship between each explanatory component and the CO_2 emissions at specific quantiles. However, this technique has limitations in terms of causal relationships between *ENEF* and CO_2, as well as between *GDP* and CO_2 emissions. As a result, we used Granger's causality test (1969). Although the regression model often reflects 'simple' correlation, Granger (1969) hypothesised that in economics, causation might be measured by assessing the ability of a time series to accurately predict future values given the values of previous time series. This test may be run on I(0) or I(1) data. To examine the null hypothesis that z does not Granger cause x, it is necessary to select the appropriate lagged values of x for inclusion in a univariate autoregression of x.

$$x_t = \theta_1 + \theta_2 x_{t-1} + \theta_3 x_{t-2} + \ldots + \theta_m x_{t-m} + \varepsilon_t, \tag{11}$$

The augmented autoregression based on the incorporation of lagged values of z is given as:

$$x_t = \theta_1 + \theta_2 x_{t-1} + \theta_3 x_{t-2} + \ldots + b_p z_{t-p} + \ldots + b_q z_{t-q} + \theta_m x_{t-m} + \varepsilon_t, \tag{12}$$

All lagged numbers of z that remain independently significant based on their t-statistics are included in this model since they collectively increase the predictive power of an *F*-test regression. Here, p denotes the shortest lag length and q denotes the longest lag length wherein the lagged value of z is relevant in the preceding extended regression. If no lag values for z are retained in the regression, the proposition that z does not cause x will be accepted.

4. Results and Discussion

The results and discussion section has been initiated by calculating the descriptive statistics, as provided in Table 1. Specifically, the descriptive stats shows that the mean and median values are positive that indicates that the CO_2 emissions, economic growth, and E.N.E.F. are enhancing over the time. Yet the difference between range

Table 1. Descriptive statistics and normality.

	CO_2	ENEF	GDP
Mean	7.427380	0.765857	13.74372
Median	7.436634	0.772616	13.75092
Maximum	7.532596	0.914637	13.92845
Minimum	7.311383	0.536671	13.55269
Std. Dev.	0.080114	0.122135	0.118290
Skewness	−0.076758	−0.290296	−0.072631
Kurtosis	1.388356	1.675477	1.715344
Jarque-Bera	13.54164	10.80581	8.635785
Probability	0.001147	0.004503	0.013328

Source: estimated by author(s) from the data obtained from the given sources.

values, accounted for minimum of 7.311, 0.536 and 13.552 for CO_2, E.N.E.F., and G.D.P., respectively. While the values reached to the maximum of 7.532, 0.914 and 13.928, accordingly. This indicates that the growth of these variables is not consistent across the time, instead fluctuating. However, the fluctuation of volatility of a variable could better be understand via standard deviation that indicates the deviation of observations from the mean values. From the reported table, both the E.N.E.F. and G.D.P. have higher standards deviation as compared to the CO_2 emissions. This reveals that global CO_2 emissions are relatively stable than the global G.D.P. and global E.N.E.F. Moreover, the skewness and Kurtosis are found varied than their critical values, i.e., 1 and 3, which illustrates that the valuables are abnormally distributed. In order to comprehensively analyse the distribution of variables, this study also employed the Jarque and Bera (1987) normality test. The estimates results are found statistically significant for CO_2, E.N.E.F., and G.D.P., respectively. Thus, the proposition of normal data distribution is rejected here and it is concluded that the data is irregularly distributed. Since the data is following asymmetric distribution: therefore, it is important to utilise appropriate long-run estimator that could deals the issue of non-normality or asymmetric distribution of the variables. In this sense, the current study uses the novel Q.Q. regression, which combines the traditional linear regression and standard quantile regression and evaluates the effect on different quantiles of dependent as well as independent variables (Cleveland, 1979; Stone, 1977). Besides, the said specification also holds the property of dealing the non-linearity issue of the time-series.

For a time-series data analysis, it is important to see whether the data is stationary, that could allow for further estimation. In this sense, current study two unit root tests, including the A.D.F. (1979) and the Phillips-Perron unit root tests. The estimated outcomes of both the tests are presented in Table 2. All the three variables, i.e., CO_2, E.N.E.F., and G.D.P. are found non-stationary since these variables satisfy the null hypothesis, indicates the presence of a unit root in the leveled data [I(0)]. However, when these variables are tested on the first differenced [I(1)] data. This time, the statistical values of all variables are found statistically significant at 1%, that rejects the null hypothesis of 'the unit root presence'.

Once the stationarity of variables is confirmed, this study further analyses the cointegration between the variables under-consideration. In this regard, two separate models have been tested via employing the Bayer and Hanck (2009) combined cointegration test that considers cointegration tests of Engle and Granger (1987), Johansen

Table 2. Unit root test results.

Augmented Dickey-Fuller test statistic		
Variables	I(0)	I(1)
CO_2	−1.513	−4.320***
ENEF	0.206	−5.321***
GDP	−0.263	−5.522***
Phillip-Perron Unit Root Test		
CO_2	−1.045	−4.897***
ENEF	−0.055	−5.157***
GDP	−0.569	−2.601***

Note: Significance level is denoted by *** for 1%, ** for 5% and * for 10%. I(0) is for level, and I(1) is for the first difference.
Source: estimated by author(s) from the data obtained from the given sources.

Table 3. Bayer-Hanck cointegration (2013) analysis.

Cointegration between CO_2 *and ENEF*			
Engle-Granger (EG)	Johansen (J)	Banerjee (Ba)	Boswijk (Bo)
−2.509	20.179***	−2.999*	9.153
EG-J			EG-J-Ba-Bo
12.618**			22.013**
Cointegration between CO_2 *and GDP*			
Engle-Granger (EG)	Johansen (J)	Banerjee (Ba)	Boswijk (Bo)
−2.343	22.107***	−4.653***	23.497***
EG-J			EG-J-Ba-Bo
13.600**			45.025**

Note: Significance level is denoted by *** for 1%, ** for 5% and * for 10%.
Source: estimated by author(s) from the data obtained from the given sources.

(1991), Banerjee et al. (1998), and Boswijk (1994) combinedly, where the simultaneous testing could be inconsistent (Shahbaz et al., 2018). The examined outcomes of the said test are reported in Table 3. Firstly, the cointegration results for CO_2 and E.N.E.F. is found significant as the Johansen (1991), Banerjee et al. (1998), EG-J, and EG-J-Ba-Bo are statistically significant to reject the proposition of no cointegration between these variables. Also, the Johansen (1991), Banerjee et al. (1998), Boswijk (1994), EG-J, and EG-J-Ba-Bo statistics are found statistically at 1% and 5% – leads to the rejection of null hypothesis of no cointegration between CO_2 and G.D.P. Hence, it is concluded that the long-run cointegration exist between CO_2 and ENEF, and CO_2 and G.D.P., which allows this study to analyse the long-run association between these variables.

Nonetheless, the cointegration association exist between the variables under-consideration, which allows this study to analyse the long-run relationship between variables global G.D.P. and CO_2 emissions. The estimated outcome of relation between mentioned variables is provided in Figure 1. From the results, it is noted that there is a positive and statistically significant association between global G.D.P. and CO_2 emissions across the quantiles. Specifically, the coefficient value is found 50–200, that demonstrate that enhancement in the G.D.P. significantly increases global CO_2 emissions. These estimates are found consistent to the study of Shikwambana et al. (2021), Shabani et al. (2022), and Mohsin et al. (2022) by validating the positive nexus between the two. The reason of positive association between the two is that the higher level of income enhances the investment and per capital income level, that

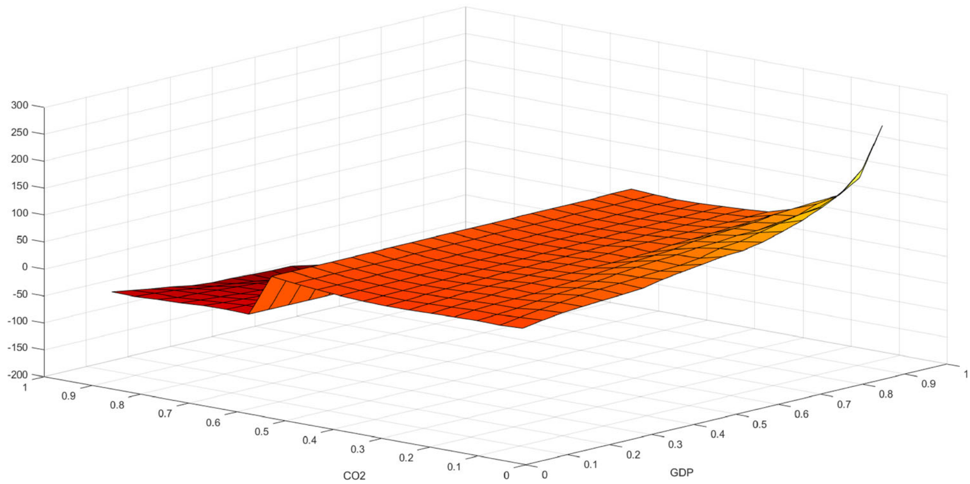

Figure 1. QQ results for GDP and CO_2.
Note: The z-axis indicates the coefficient values, the x-axis indicates GDP, and the y-axis represents CO_2.
Source: estimated by author(s) from the data obtained from the given sources.

boost economic activities and results in the industrial expansion. However, immense production and industrial expansion needs more energy to fulfill demand, which is obtained from tradition fossil fuels. Consumption of such non-renewable energy sources has a major drawback, i.e., these energy sources are the major sources of CO_2 emissions in the environment. Hence, the economic growth is a prominent factor of environmental degradation. On the other hand, the results of this study are contrary to the empirical results of Mahapatra and Irfan (2021) and Brännlund et al. (2007), that validates adverse impact of E.N.E.F. on emissions due to lower level of tax and industrial structure. Besides, most of the developed and developing economies across the globe are still using these traditional energy sources as their primary energy source. Hence, the environmental quality of the globe is rapidly degrading, which must be controlled via appropriate policy measures.

E.N.E.F. is considered as important environmental factor of environmental sustainability in the literature. However, to test the statement, the empirical results of Q.Q. regression is reported in Figure 2. The examined results reveals that there is a mixed association between E.N.E.F. and CO_2 at different quantiles. Specifically, in the lower quantiles (0–0.3) of E.N.E.F. and (0–0.6) CO_2, there is a weaker association regarding enhancement of the CO_2 emissions. However, this association is stronger medium (0.6–0.8) quantiles, that indicates that there is a positive and significant association between the two. Yet, the higher quantiles of CO_2 report negative coefficient values that indicates increasing E.N.E.F. significantly and negatively affects the global CO_2 emissions. The coefficient value for negative impact is noted as 0–100. Thus, the higher level of E.N.E.F. could lead the global towards a low carbon. Such findings are in line to the existing study of Özbuğday and Erbas (2015), Muhammad and Saad (2018), Akram et al. (2020), and Akram et al. (2022), that empirically validate E.N.E.F. as viable solution for environmental sustainability and emissions reduction. However, the empirical results of this study is contrast to the empirical results of Akram et al. (2020), Salari et al. (2021), and Olayungbo et al. (2022), where these

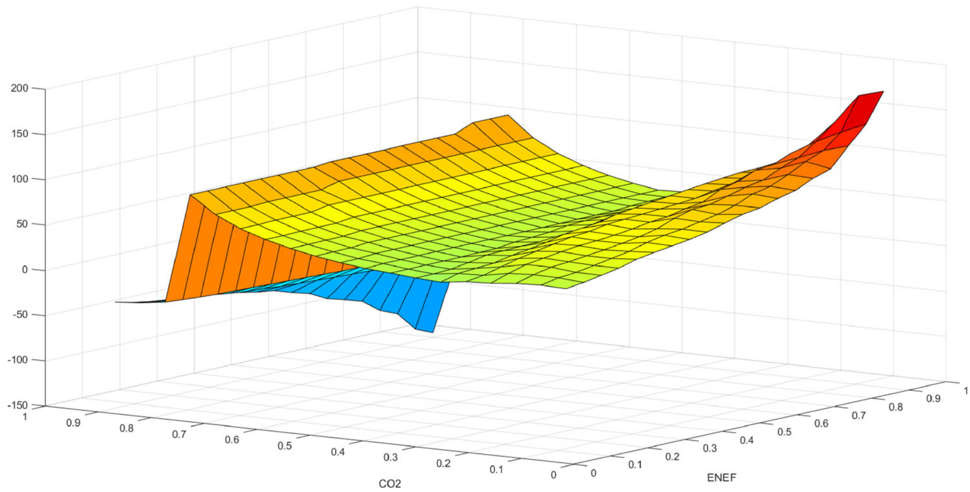

Figure 2. QQ results for ENEF and CO_2.
Note: The z-axis indicates the coefficient values, the x-axis indicates ENEF, and the y-axis represents CO_2.
Source: estimated by author(s) from the data obtained from the given sources.

Table 4. Pairwise Granger-Causality test.

Null hypothesis:	F-Statistic	Prob.
ENEF − CO_2	5.45859	0.000
CO_2 − *ENEF*	2.56562	0.004
GDP − CO_2	2.76646	0.026
CO_2 − *GDP*	0.80596	0.723
GDP − *ENEF*	3.43067	0.000
ENEF − *GDP*	2.69781	0.003

Note: Significance level is denoted by *** for 1%, ** for 5% and * for 10%.
Source: estimated by author(s) from the data obtained from the given sources.

studies claimed increased economic growth leads toward the adoption of energy efficient and renewable energy resources, which improves environmental quality. Indeed, most of the energy resources across the globe is still fossil fuel energy oriented. Yet the technological advancement helped improve the productivity of products and equipment, that uses less energy to provide the same amount of output. Hence, the energy consumption reduces, that directly affect the level of increased CO_2 emissions.

The Q.Q. regression provides evidence of the association between G.D.P. and CO_2, and E.N.E.F. and CO_2, still the causal association is not described by that specific method. In this regard, current study employs pairwise Granger causality test proposed by Granger (1969). The estimated results are reported in Table 4. From the results, it is noted that there is a unidirectional causal impact from G.D.P. to CO_2. This indicates that enhancement in the economic growth encourages economic activities. As a result, emissions of CO_2 boosts, that plays a major role in environmental degradation. This stance is supported by the studies of Salari et al. (2021) and Olayungbo et al. (2022), that empirically reveals that economic growth triggers environmental degradation. On the other hand, increased level of income also promotes various environmental protection measures, including E.N.E.F. As a result, there is a two-way causal nexus between E.N.E.F. and economic growth captured via G.D.P.

Whereas this increased level of E.N.E.F. not only contributes to global economic growth, but also reduces CO_2 emissions. The test validates bidirectional causal nexus between E.N.E.F. and CO_2 emissions, at 1%, 5%, and 10% level of significance. Such findings are consistent to earlier empirical studies such as Khan et al. (2021), Mirza et al. (2022) and Hassan et al. (2022). Hence, from a policy perspective, both G.D.P. and E.N.E.F. could play an important part in reducing the emissions level and promoting environmental sustainability.

5. Conclusion and Policy Implications

Environmental sustainability and emissions reduction are some of the critical targets of the global economies. However, in order to maintain raid economic growth, economies are still using non-renewable energy resources, which although enhances economic growth but at the cost of environment. Keeping in view the mentioned issues, this study investigates the association between economic growth, E.N.E.F. and environmental quality from a global perspective over the last three decades. The estimated outcomes reveals that the long-run equilibrium relationship exist between the variables. Therefore, this study uses novel time-series approach (Q.Q. regression). The estimated results asserted that economic growth is a significant factor of CO_2 emissions at all quantiles. Since the economic activities across the globe are rapidly increasing, which is relying in energy. However, using fossil fuel as a cheaper source of energy leads to enhance the CO_2 emission level globally. On the other hand, the study found that E.N.E.F. could be a viable solution to the increased environmental issues. Specifically, the use of E.N.E.F. resources tends to reduce the use of energy intensive products and provides the same amount of output while consuming lesser amount of energy. As a result, the use of energy reduces, that consequently leads to the reduction of CO_2 emissions in the atmosphere. Hence, the global economy moves toward carbon neutrality.

Based on the empirical outcomes, this study suggested policies that could be advantageous for economic as well as environmental sustainability. Specifically, this study recommends policymakers to promote investment in the E.N.E.F. sector. Besides, other financial support in the shape of subsidisation shall also be encouraged towards the E.N.E.F. sector. Implementation of E.N.E.F. in the industrial sector could enhance the productivity level without increasing demand for energy. Therefore, this could be a viable solution to overcome environmental degradation. In addition, this study noted that economic growth is the leading factor of increased carbon emissions. Therefore, it is suggested that the increased economic growth shall be utilised in a sense that it encourages the use of environmentally friendly energy resources and minimise the use of environmentally destructive resources. For this purpose, the policymakers must encourage investment in technologies and research and development, which further strengthens the E.N.E.F. sector.

Notes

1. See https://controls.papercept.net/conferences/conferences/CNCA19/program/
2. See https://data.worldbank.org/indicator/NY.GDP.MKTP.KD

Disclosure statement

No potential conflict of interest was reported by the authors.

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