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Analyzing the Effects of Renewable and Nonrenewable Energy Usage and Technological Innovation on Environmental Sustainability: Evidence from QUAD Economies

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Abstract: The following study examined how energy use and technological advancement impacted environmental sustainability in QUAD (US, Japan, Australia, and India) economies between 1991 and 2021. The study considers the generation of renewable energy, fossil fuel use, and the effects of economic expansion on environmental sustainability. The research used the moment quantile regression technique based on the outcomes of slope heterogeneity, cross-sectional dependence, and the order of the unit-root by the using second-generation method of cross-sectional augmented Im, Pesaran, and Shin tests. The study discovered that renewable energy production and technological innovation enhances environmental sustainability, whereas the use of nonrenewable energy and economic growth worsen it. When implementing policies regarding the environment, energy, and the growth of QUAD economies based on concrete evidence, policy makers and environmentalists in QUAD countries should also take into account the asymmetrical performance of efficiency in energy production, technological innovation, and economic growth.

Keywords: QUAD countries; fossil-fuel energy; renewable energy; greenhouse gases; method of moments quantile regression (MMQR)

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1. Introduction

The "UN Chartered of Convention on Global Climate Change's 2015 Paris Agreement" proved to be a historic step towards the devastating impact on climate change. On 4 November 2016, the agreement came into effect after being approved by 147 countries. This treaty's main goal is to reduce GLOBAL GREENHOUSE GAS (GHG) emissions while maintaining a 2 °C increase in annual average temperature [1,2]. One of the prominent contributors to the effects of GHG on the planet is CO_2 emissions, where the Industrial Revolution led to a historical increase in greenhouse gases.

Indo-West-Pacific cooperation, particularly the industrialized QUAD countries, are the main sources of concern. While pursuing sustainable options, QUAD nations have ratified the convention. According to their level of development, which determines industrial growth, the QUAD is significant for the ecology and causes the concerned country to use temporary remedies. According to the Emission Database for Global Atmospheric Research, the USA contributes 4535 Mt to the global CO_2 emissions, India contributes 2411.73 Mt, Japan 1061.77 Mt, and Australia 386.44 Mt [3]. Most of the QUAD member nations still have a long way to go before they can be considered "green," and significant changes to climate issues are required. Therefore, knowing the causes of greenhouse gases and establishing an association between energy consumption, greenhouse gases, and economic growth are necessary for QUAD nations to develop appropriate environmental and EG policies. The economies of the QUAD have seen exceptional development over the preceding two decades. The QUAD nations considerably impacted world greenhouse gases in 2020 and provided 28% of global growth and 42% of global consumption of energy. The carbon emission ratio of the QUAD countries climbed from 41.66 to 53.11 percent between 2010 and 2020, and they now represent 53.01 percent of global emissions. In 2020, the total growth of the QUAD economies was 29.959 trillion USD or 31.53% of global economic growth. Additionally, India was the third-largest exporter in the world with total trade exports of 284 billion US dollars [4]. Therefore, this study considers prior research and combines some of the many literatures in the context of the QUAD nations. This sets our article apart from the competition in terms of value. Additionally, our model breaks down energy use into the use of fossil fuels and the generation of power from renewable sources on the environment of QUAD countries [1,5,6].

Theoretically, this study tries to discover that the extensively researched connection between consumption of energy, innovation and economic growth in the QUAD which differs for each of the listed countries and that there is a bunch of research accessible for each country individually but not for the QUAD [7–12]. This research looks at the effects of energy use and technology innovation on environmental sustainability from 1991 to 2021 for the USA, Australia, Japan, and India. This study also examines a hitherto unresearched topic: the impact of renewable energy generation on greenhouse gases in the QUAD nations [13–15]. Methodologically, this paper employs a novel and complex econometric technique, including unit root approaches and second-generation cointegration. The following tests were applied in this study: the "Westerlund error correction mechanism" (WECM) test, the "Dumitrescu-Hurlin panel causality tests", the "Method of Moment Quantile Regression" (MMQR), the "Pesaran slope heterogeneity", the panel unit-root, and "cross-section dependence tests."

Section 2 explores further earlier theoretical and empirical literature. Section 3 discusses the factors, data retrieval sources, the theoretical framework, highlighting the assumed model, and relevant approaches. Section 4 delves deeply into the useful conclusions. Based on the findings, the Section 5 concludes with important policy suggestions.

2. Literature Review

Research on the relationship between energy consumption (EC) and economic growth (EG) is categorized into three groups for this analysis: research on the relationship between (1) EG and GHG, (2) the dynamic link between EG, GHG, and EC, and (3) green-house gases (GHG) and technological innovation (TECH). Each of these three categories of study will be covered in the current section, which will not only pave the path for us to choose the list of variables, but also give us a theoretical reasoning for this study to choose its optimal list of variables.

2.1. Greenhouse Gases and Economic Growth

The interest in examining growth strategies in connection to climate change has grown over the past two decades, with such studies focusing on global warming and the greenhouse gases. When we take into account the research that examines the link between economic growth and CO_2 emissions in the selected nations as whole, the amount of economic literature on CO_2 emissions and growth has reduced rather than increased. Even though there has been many research looking into the state of climate change and global warming separately, there have been relatively few studies looking into the connection between economic development and CO_2 emissions. However, there is research indicating that the energy growth conundrum is often examined from the standpoint of harm to the environment [12,16,17].

Most of the papers examined the connection between economic development and CO_2 emissions in the debates held under the heading of developing a growth theory that should be connected to the goal of lowering CO_2 emissions [18–20]. According to Azam et al. [21], there is a correlation between CO_2 emissions and economic growth in China, Japan, and the USA [22]. They analyzed the environment degradation proxied by CO_2 emission on the profile of chosen higher CO_2 emissions economies. According to Liu et al. [23], energy consumption has a positive and statistically significant influence on CO_2 emissions for BRIC nations in the long-term equilibrium. Numerous studies looked at the connection between CO_2 emissions and economic growth at the national level. Yousefi-Sahzabi et al. [24] investigated the relationship between CO_2 emission and economic growth in Iran and found a strong positive correlation, while Bouznit et al. [25] also found the same results on the profile of Algeria. According to Magazzino [26], Israel's real growth is what determines the country's energy consumption and CO_2 emissions. Studies such as those by Kluschke et al. [27] analyze the state of CO_2 emissions and associated costs for various technologies.

Between 1992 and 2010, in European Union Member States and listed nations, research on the connections between greenhouse gases, energy usage, trade, urbanization and economic development was conducted by Kasman and Duman [28]. There is a one-way causal link between EC, trade, urbanization and GHG, as per the outcomes of the "panel-causality test", the "unit-root test", and the bench cointegration approach. There is a causal relationship between "fossil-fuel energy consumption" (FEC), urbanization, and EG, trade, energy demand, urbanization, and investment. The contributions of long-term greenhouse gases, EC, trade, and EG are all different. Begum et al. [29] examined the connection among EG and GHG from 1970 to 2009 in Malaysia. The ARDL-DOLS (dynamic ordinary least squares) technique has significantly increased greenhouse gases as a result of global economic activity. China served as the sampling field for Long et al. [30] data cointegration examination from 1952 to 2012. The study's findings showed a link between EG and greenhouse gases as well as a bi-directional association between EG and greenhouse gases. Niu et al. [31] further investigated EG, REG, and GHG reduction from 1971 to 2005 for eight Asian-Pacific countries. The use of a panel VECM and a Granger-causality test found a significant link between EG and greenhouse gases.

2.2. The Association between EG, EC, and GHG

This study examines the strong connection between EG, EC, and GHG. One of the most well-known studies in this area, Wahab et al. [32] investigated energy production with CO_2 for the G-7 nations from 1996 to 2017 used CS-ARDL. According to Wahab's research, TECH innovation and transportation of goods and services across borders has a counter relationship to GHG, just as energy production and emissions have an opposite relationship. However, there is a positive correlation between EG and trade and greenhouse gases. Additionally, Wahab et al. [32] examined RE and financial stability in connection to GHG for the BRICS countries between 1995 to 2018 using a geographic Durbin model. The findings of Wahab show that export has a negative relationship with greenhouse gases and that RE has a negative relationship with greenhouse gases as well. Imports and EG have a favorable association with regard to greenhouse gases. Additionally, Ang [33] used French data from 1960 to 2000 to examine the strong causality between EG, EC, and pollution using the cointegration technique and ECM. A long-term link between the three parameters was found by the researcher. EG and EC both have a short-term one-way causal relationship. Chen et al. [34] examines the dynamic link in China using the DOLS methodology and highlights that trade liberalization and energy efficiency reduce GHG. The elasticity of GHG in response to EC is predicted to be 1.101–1.175%, whereas the elasticity of GHG about trade is predicted to be 0.144–0.160%.

The examination of the United States by Soytas et al. [35] is another noteworthy piece in this collection. The Granger causality test is employed by the researchers to establish that wealth, not GHG drive EC. This finding suggests that, in light of the current environmental crisis, EG may not be the best course of action. Halicioglu [36] also examines the dynamic connection between EG, EC, and pollution. [36] uses bound-testing and cointegration techniques to investigate the relationship in Turkey from 1960 to 2005. The study shows that there is a long-term relationship between GHG, EG, and international trade, as well as a longer-term relationship between GHG, EG, and income. To reduce GHG, Turkey's EG strategy needs to consider environmental disasters, according to the projected results.

When analyzing the causative relationship between EC, EG, and GHG in research on the BRICS, panel causality analysis is used to account for "cross-sectional dependency" among BRICS countries [37]. Experts claim that the EKC theory is exclusively true for Russia. Additionally, there is an asynchronous correlation between greenhouse gases and EG in Brazil but a bidirectional causality between the two in South Africa. In contrast to the other nations, India showed unidirectional causation between power use and greenhouse gases [37,38]. Sebri and Salha [15] examined the link between EG, RE use, greenhouse gases, and the volume of international trade in the BRICS between 1971 and 2010 using DOLS and completely modified DOLS and found cointegration among the mentioned variables. The Granger Causality test is also being used by researchers to determine whether there is a causal link between RE usage and EG. Researchers claim that RE is essential for EG and environmental policy in the BRICS [39–41]. Second, this analysis is the first to look at how the BRICS nations are affected by the FEC, REG, and greenhouse gases. Third, this research provides insightful analyses on the causal association between FEC, REG, TECH, and GHG in the BRICS nations. Policymakers may use this knowledge to find efficient carbon-reduction tactics. Fourth, the bulk of earlier investigations, Rahman et al. [42]; Khan et al. [43]; and Liddle [44–49] utilized the EKC theory and the STIRPAT model.

2.3. Greenhouse Gases and TECH

Wahab et al. (2021) [32] evaluated TECH for the G-7 countries from 1996 to 2017 with trade-adjusted greenhouse gases. They also used AMG and CCMG for hardness. Technical innovation and greenhouse gases are inversely related, and export also has a negative association, according to Wahab's research. On the other hand, imports and EG have a favorable impact on greenhouse gases. Wang et al. [50] evaluated the N-11 nations' greenhouse gases, EC, financial development, and technological innovation. The study found a correlation among EG, financial evolution, and greenhouse gases that are favorable. The usage of TECH and renewable energy generation (REG) is connected with increased emissions of GHG. Further, the study by Wahab et al. [51] explores how sustainable technology affects green growth. His research examines the impact of sustainable energy on EG in the BRICS nations by controlling the usage of RE and non-RE. In the study, endogeneity, cross-sectional dependency outcomes, and complex panel-data-prediction methodologies by a rising degree of heteroskedasticity are used. Empirical data suggests that technology advancement related to the environment has a substantial impact on EG. The study contends that whereas non-renewable energy stifles green growth, REG fosters long-term development. The study suggests that BRICS countries should develop their energy technology to accomplish EG while being environmentally conscious. Su et al. [52] investigated the impact of TECH and transportation of goods and services across-border on US CCO2 covered the period between 1991 and 2017. This study made use of the ARDL methodologies, "Phillips–Perron", ADF tests, and "Zivot–Andrews root test." The study's conclusions indicate that the aforementioned variables have a complicated relationship with greenhouse gases from TECH, which change depending on consumption. Depending on how they were used, exports and greenhouse gases led to noteworthy outcomes. The study also discovered that TECH helps reduce greenhouse gases.

3. Data and Methods

Data Description

The objective of this study is to apply novel research methodologies for estimating the effects of EC on the GHG using data of QUAD economies between 1991 and 2021. This analysis takes a novel approach in that it makes use of fresh exogenous variables like FEC usage and output from REG sources. To get at the outcomes, this study also makes use of a latest econometric methodology. The best region to use as a sample for this study is the list of QUAD nations, represented by "*i*" from 1991 to 2021, denoted by "*t*" and variables notations and its measurements are listed in Table 1. The current research concentrated on the period 1991–2021 since the most recent data for all nations was readily accessible.

Additionally, subscription "i" stands for the country while years 1991 through 2021 are represented by the subscription "t" for this study.

Table 1. Variables and its description.

Variable	Explanation and Unit	Source
GHG	Greenhouse Gases in kilogram	Global Carbon Atlas
EG	Economic growth as GDP of the country at constant 2015 US$	WDI
FEC	Fossil-fuel energy consumption as % of total energy consumption (Thousand tonnes oil equivalent)	WDI
REG	Renewable energy generation as % of total energy consumption (Thousand tonnes oil equivalent)	WDI
TECH	As number of patents registered by the locals and non-local residents of particular country	WDI

The basic econometric equation is as follows:

$$GHG_{it} = \vartheta_0 + \vartheta_1 EG_{i,t} + \vartheta_2 FEC_{i,t} + \vartheta_3 REG_{i,t} + \vartheta_4\ TECH_{i,t} + \in_{i,t} \quad (1)$$

The present study, which has a significant speculative rationale, is mainly accountable for the usage of the variables in the Equation (1). Every nation where commodities are purchased contributes to greenhouse gases. It is crucial to consider the influence of trade when examining variables that raise or decrease greenhouse gases in QUAD nations. FEC power plants create heat, then transformed into steam and used to power turbines that generate energy. When FEC are consumed, a considerable volume of carbon is extracted. Extreme climate variation causes extreme amount of GHG, which intake heat in the surrounding. Unlike FEC, EC has a positive relationship with GHG, $\vartheta_1 = \frac{\partial GHG_{i,t}}{\partial FEC_{i,t}} > 0$. According to prior research, the correlation is positive, implying that increasing per capita EG leads to greater greenhouse gases. Some contend that even when EG reaches a certain level, there is no tipping point where GHG start to decline. Although they might pave the way for higher industrial productivity, EG increases do not seem to reduce net GHG. However, as EG rises, a structural change occurs, resulting in a decrease in poverty, a constantly rising proportion of manufacturing services, and an increase in the urban population. Therefore, the link between EG and greenhouse gases is expected to be positive, $\vartheta_2 = \frac{\partial GHG_{i,t}}{\partial EG_{i,t}} > 0$. As previously stated, REG is expected to have a negative connection with GHG. Geothermal energy hydropower, wind, biomass, and solar may all be used as REG while lacking any unwanted contribution to GHG as FEC does, therefore $\vartheta_3 = \frac{\partial GHG_{i,t}}{\partial REG_{i,t}} < 0$. Correspondingly, TECH is an essential issue; TECH enhances enterprise efficiency and productivity as well as assisting businesses in transitioning to RE [53–55]. Whereas most research focuses on the direct impact of TECH on GHG, TECH may be viewed as an accelerating component that enhances the relationship between GHG and their causes. Innovation in TECH is likely to influence EC, which in turn influences GHG emissions. TECH is strongly related to GHG and is becoming increasingly prominent with advancement in TECH in reducing GHG and enhancing environmental conditions [56–58]. CO_2 emissions from consumption are expected to be negatively related to TECH, which is crucial for lowering greenhouse gases, such as $\vartheta_4 = \frac{\partial GHG_{i,t}}{\partial TECH_{i,t}} < 0$ [6,59,60]. In a nutshell, the intended outcome is $\vartheta_1 > 0$, $\vartheta_2 > 0$, $\vartheta_3 < 0$ and $\vartheta_4 < 0$.

Table 2 contains the descriptive data. We determined the maximum GHG outcome was 7.6, whilst the minimum outcome is 5.8. The average rating for greenhouse gases innovation was 6.7 [61]. The average EG value was 13.45, with lowest and highest values of 12.90218 and 14.3998, respectively. The FEC had a mean value of 2.415808 and a minimum and maximum value of 2.271724 and 2.532649, respectively. The average amount of REG used was 1.993511, with a low of 1.643493 and a high of 2.541893. TECH had a minimum and highest reading of 4.096854 and 6.750405, respectively. The mean value of TECH was discovered to be 5.107022.

Table 2. Descriptive statistics.

	GHG	EG	FEC	REG	TECH
Mean	6.691685	13.45143	2.415808	1.993511	5.107022
Median	6.744789	13.35257	2.425058	1.828813	5.023638
Maximum	7.575724	14.3998	2.532649	2.541893	6.750405
Minimum	5.859555	12.90218	2.271724	1.643493	4.096854
Std. Dev.	1.04142	1.589474	0.650556	0.872234	1.16586
Skewness	0.701301	2.331835	0.424857	1.523995	1.686952
Kurtosis	2.74927	4.886113	2.047683	2.637125	4.722404
Jarque-Bera	4.100074	26.34848	11.91718	22.38961	31.25287
Probability	0.175524	0.005004	0.008422	0.005018	0.005

Table 2 displays the average outcomes, volatility, and range for each variable, as well as a normality check. According to the statistics, GHG are the most variable, followed by EG, FEC, REG, and TECH. Furthermore, Jarque–Bera (JB) results reveal that the data are not normally distributed by rejecting the null hypothesis of normal distribution for GHG, EG, FEC, REG, and TECH. The outcomes are statistically significant at three levels: 1%, 5%, and 10% for each variable.

4. Econometric Analyses

The primary objective of the current study is to apply the novel techniques for calculating the effects of EC on GHG. Thus, it takes a distinctive tack while using an original econometric methodology for performance as well as including FEC use and REG as contemporary independent variables [62]. For this purpose, this study will initially evaluate the data by different diagnostic techniques listed in the upcoming section.

4.1. Slope Heterogeneity and Cross-Sectional Dependency Tests

The current study started its analyses with the slope heterogeneity (SH) and Cross-sectional dependency (CSD) tests. The null hypothesis of the SH test is that the data are not normally distributed. Additionally, a Pesaran [63–66] test for CSD as per Equation (4) and Pesaran and Yamagta [67] test for SH coefficients (Equations (2) and (3)) were conducted. Utilizing suitable stationary testing is the next step after these problems have been found. The absence of spillover effects and the independence of cross-sections are the test's null hypotheses. In other words, the nations can withstand local and international economic crises because they are self-sufficient. Before employing unit root, cointegration, or long-run estimation, it is essential to first pinpoint these problems using the econometric tools mentioned above. In the absence of these worries, the results could produce biased results.

$$\tilde{\Delta}_{Slope-Heterogeneity} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - k\right) \tag{2}$$

Whereas, T represents the time series dimension, N is the cross section dimension, "k" is the degree of freedom, $\widetilde{S}$ is the weighted indifference; the adjusted delta tilde value can be obtained by using Equation (4).

$$\tilde{\Delta}_{Adjusted-Slope-Heterogeneity} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - 2k\right) \tag{3}$$

CSD is given as

$$CSD_{LM-Adjusted} = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{k=i+1}^{N}\hat{\gamma}_{ik}\right)\frac{(T-j)\hat{\gamma}_{ik}{}^2 - E(T-j)\hat{\gamma}_{ik}{}^2}{V(T-j)\hat{\gamma}_{ik}{}^2} \tag{4}$$

As demonstrated in Table 3, the econometric findings of QUAD economies have different slope coefficients, as shown by $\tilde{\Delta}$ and $\tilde{\Delta}_{Adjusted}$ with values of 14.261 *** and 15.823 ***, respectively. This demonstrates that these nations differ in terms of EG, FEC, REG, TECH, and GHG. Similarly, the findings of the CSD test are shown in the lower half of Table 2. This means that independence is unusual in the modern era and that the majority of economies are interdependent.

Table 3. Slope Heterogeneity and Cross-sectional Dependency tests.

Heterogeneity/Homogeneity Check.		
Statistics	$\tilde{\Delta}$	$\tilde{\Delta}_{Adjusted}$
	14.261 ***	15.823 ***
Cross − Sectional Dependence		
GHG	EG	TECH
7.923 ***	16.501 ***	10.831 ***
FEC	REG	-
1.126 **	−1.757 **	-

*** (1%) and ** (5%).

Conducting stationary testing is the next step after these issues have been identified. The assumption under test is that the cross-sections are distinct and that there are no spillover effects. In other words, the nations are self-sufficient and resistant to regional and international economic shocks. Applying the aforementioned econometric tools, it is vital to identify these issues before using unit root, cointegration, or long-run estimation. Without taking these factors into account, the results can be biased.

4.2. CIPS and Westerland Cointegration Tests

The cross-sectional augmented Im, Pesaran, and Shin (CIPS) technique (Equation (5)) is used to test for stationarity [64]. By using CADF, or cross-sectionally augmented Dickey Fuller, this test is able to handle CSD and a variety of slope coefficients. Therefore, this method is advised above conventional panel unit root testing, which only address one of the two issues mentioned above. The standard equational form for the CIPS test is as follows:

$$\widehat{CIPS} = \frac{1}{N}\sum\nolimits_{i=1}^{N} CADF_i \quad (5)$$

The findings of this study's unit root test are shown in Table 3 as the stage below.

Table 4 displays the empirical results of the CIPS test. Where the test's outcomes lack any affect by non-normality or CSD. All selected factors are found to be stationary at first difference and non-stationary at the level. Which shows that the means of these selected factors are not zero. Additionally, EG, FEC, REG, and TECH all fluctuate at different rates. As a result, depending on the cross-section, these properties appear to change. As a result, all variables are now stationary at I(1).

Table 4. Unit Root Test.

Statistics	**Trend and Intercept**	
	I(0)	**I(1)**
GHG	−2.412	−4.9973 ***
EG	−2.252	−4.0573 ***
FEC	−1.832	−6.2673 ***
REG	−2.872	−6.7373 ***
TECH	−3.092	−5.8173 ***

*** (1%).

Correspondingly, the error correcting mechanism's cointegration approach (ECM) is applied. As indicated earlier, the Westerland test is beneficial for generating efficient outcomes even at varying slope coefficients, as well as the problem of CSD.

$$G_t = \frac{1}{N}\sum_{i=1}^{N} \frac{\alpha_i}{SE\alpha_i} \tag{6}$$

$$G_t = \frac{1}{N}\sum_{i=1}^{N} \frac{T\alpha_i}{\alpha_i(1)} \tag{7}$$

$$P_t = \frac{\alpha}{SE(\alpha)} \tag{8}$$

$$P_t = T\alpha \tag{9}$$

where Equations (6) and (7) are group-mean-statistics while Equations (8) and (9) are panel statistics. Rejection of the null hypothesis requires cointegration for at least one cross-sectional unit in each panel.

Table 5 displays the results of a cointegration test with an error correction technique (ECM). Gt, Ga, Pt, and Pa are the group and pane statistics findings. The data show that EG, FEC, REG, TECH, and GHG have a long-run cointegrating connection.

Table 5. Cointegration Testing.

Statistics.	Value	*p*-Value
G_t	−8.894 ***	0.004
G_a	−15.589 ***	0.084
P_t	−16.347 ***	0.004
P_a	−16.115 ***	0.008

*** (1%).

4.3. Method of Moments Quantile Regression (MMQR)

The outcomes of the homoscedasticity tests depict the absence of homoscedasticity. As a result, the longitudinal quantile approach is utilized to examine the heterogeneous and distributional influence throughout quantiles, Sarkodie and Strezov [10]. The fundamental study by Koenker and Bassett [68] proposed the "panel quantile regression" approach [69]. In general, "quantile regressions" are utilized to examine the conditional median or varied quantiles of the endogenous variables subject to certain exogenous variable outcomes, as opposed to regular least-squares regressions, which consist of coefficients of the conditional mean of the dependent variables following certain exogenous variable values. "Quantile regressions" are comparatively resilient to outliers in estimate It is also beneficial when the relationship between the conditional means of numerous variables is weak or non-existent [70–72]. This analysis, however, used the Machado and Silva [14] MMQR with fixed effects. While resilient to outliers, quantile regression lacks to account for possible unobserved variability between particularly in a specific panel. The MMQR technique identifies the conditional heterogeneous covariance influences GHG emission by enabling particular impacts to affect the whole equation rather than simply varying means [73]. The MMQR estimation methodology is especially beneficial while the panel data model has endogenous and explanatory factors and integrated with specific effects. The MMQR method is similarly simple to apply since it produces non-crossing outcomes of the regression quantiles. The conditional quantiles $Q_y(\frac{\tau}{X_{it}})$ for a model of the location-scale variation are estimated as follows:

$$Y_{it} = \alpha_i + X'_{it}\beta + \left(\delta_i + Z'_{it}\gamma\right)U_{it} \tag{10}$$

When the probability $P\{\delta_i + Z'_{it}\gamma > 0\} = 1$. $(\alpha, \beta', \delta, \gamma')$ are parameters that must be calculated, (α_i, δ_i), $i = 1, 2, 3, \ldots, n$, where Z is a k-vector of identifiable components of X that are differentiated transformations l with element "i" provided by

$$Z_l = Z_l(X),\ l = 1, 2, 3, \ldots .k \tag{11}$$

X_{It} is distributed independently and identically for any fixed "i" and is time independent "t". U_{It} is distributed independently and identically among individuals (For further details on limit and derivation of quantile, one may read Mavrakakis and Penzer [74] and Machado and Silva [14] (2019)) "i" and throughout time "t" and is orthogonal to X_{It} and normalised to fulfil the moment criteria in Machado and Silva [14], which do not necessitate stringent exogeneity. Consequently, Machado and Santos Silva [14] MMQR approach employed. Despite its non-normality robustness, the basic quantile regression approach overcomes the problem of unobserved variability inside the specific panel. This approach may also be utilized to assess the conditionally heterogeneous covariance effect of FEC and REG on GHG emissions when they are combined with TECH and EG. Indirect impacts may extend across the distribution [75,76].

This method works just as well when endogenous independent variables are present in the model [54,77]. The MMQR method's generic equational form is as follows:

$$Q_y(\tau/X_{it}) = (\sigma_i + \vartheta_i q(\tau)) + X'_{it}\beta + Z'_{it}yq(\tau) \tag{12}$$

X_{it} contains all independent variables like FEC, REG, TECH, and EG. The probability's distribution of GHG quantile distribution on X it is given by $Q_y(\frac{\tau}{X_{it}})$. $X_{it}\cdot\ \sigma_i + \vartheta_i q(\tau)$ is a linear-estimate that represents the quantile fixed-effect for each cross-section via τth. Furthermore, $q(\tau)$ is for the quantile derived using the optimal control problem:

$$\text{Minimize } q \sum_i \sum_t p\tau\ (R_{it} - Z'_{it}yq(\tau)) \tag{13}$$

The check mechanism $p\tau$ for any "$A > 0$" at time "T" is represented (For a detail discussion on quantiles and deriving "lower" and "higher" quantiles one must read Canay [78].

$$p\tau\ (A) = (\tau - 1)AI\{A \leq 0\} + TAI\{A > 0\} \tag{14}$$

Furthermore, the robustness tests in this study are carried out with the use of an ordinary quantile regression approach. Furthermore, the FEC and REG are combined with the TECH and EG, the panel-causality test of Dumitrescu and Hurlin [79] utilized to assess the FEC and REG's causal influence on greenhouse gases [34,80,81].

5. Results and Discussions

Table 6 displays the MMQR method findings for each quarter-based quantile, as well as the results for location-based and scale-based regressions. However, before presenting the quantile findings, this study will first provide the results of location-based and scale-based regressions, in which only EG and FEC are significant at both location-based and scale-based regressions, while all other variables are inconsequential.

Following the results given in Table 6, the FEC has a positive impact on GHG emissions, comparatively higher rise in FEC at location-based, whereas this impact drops at scale-based, implying that as FEC increases, the environment in all QUAD nations deteriorates. While EG has higher deteriorating impact on GHG at the location-level then at the scale-level, as per the results of REG, its corrective impact on GHG is larger at scale-based than the location-based. While the situation in case of REG is opposite as compared to the results of REG, such as the impact of TECH is larger at location-based then scale-based outcomes.

This analysis contains quantile-based regression for each quarter, where one can see that at higher quantiles, the influence of EG and FEC diminishes, while the other components, such as REG and TECH, which have a negative impact, exhibit an inverse trend as a GHG corrective effect. As the corrective influence of REG increases at higher quantiles, the impact of TECH decreases at higher quantiles.

Table 6. Method of Moments Quantile Regression (MMQR).

GHG	Location	Scale	$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$
FEC	3.14854 *** [0.937]	0.8524 ** [0.796]	4.87234 *** [1.567]	4.68132 *** [1.098]	4.25732 *** [0.550]
REG	−1.040446 * [0.098]	−1.05154 [0.084]	−1.0507 *** [0.166]	−1.06393 ** [0.116]	−1.0763 *** [0.058]
EG	0.99654 ** [0.399]	0.5959 ** [0.339]	2.48234 *** [0.682]	2.46132 *** [0.477]	2.41332 *** [0.236]
TECH	−0.89146 * [0.289]	−0.6254 [0.246]	−0.6214 *** [0.495]	−0.58032 * [0.346]	−0.4903 *** [0.171]
Const	−16.68946 [4.721]	0.7216 [4.762]	−16.423 *** [7.978]	−15.57568 * [5.583]	−13.68868 * [2.779]

*** (1%), ** (5%), and * (10%).

The findings of EG at each quantile reveal a declining tendency, as a unit increase in EG generates greater GHG emission, but at a decreasing trend at higher quantiles. These results are validating the concept of Anwar et al. [54] where the impact of EG on CO_2 increases at higher quantiles for ASEAN countries. The substantial variety in standard error indicates that while the QUAD union includes both Asian and Western nations, their growth rate varies for each rising quarter-based quantile. The FEC likewise has a positive but declining trend at each higher quantile, e.g., this impact is low at lower quantiles while higher at higher quantiles [82]. Whereas the variation in standard error findings indicates that each QUAD economy is suffering from increased GHG emissions owing to rising nonrenewable energy sources [83]. The results of FEC also validate the concept of Khan et al. [84] who are of the opinion that the consumption of FEC decreases as the country achieves their level of development and then tries to find alternate energy sources.

The second segment of chosen components, such as REG and TECH, have a corrective influence on GHG emissions [5,13,28,85]. Starting from the outcomes of the REG which indicates that the corrective impact of utilization of REG sources on GHG emission increases at higher quantile which is also validating our previous results where the country shifts their energy utilization option from FEC to decrease its harms on the environment with the level of development. This statement also endorses the findings of the Khan et al. [84] and Anwar et al. [54]. Finally, surprising results were observed in the case where TECH has a correcting influence on GHG emissions, but this impact decreases at higher quantiles with decreasing variation at higher quantiles. This behavior of the TECH is surprising as investment in TECH is supposed to have a corrective influence on the GHG. However, considering the simulation data, it is observed that this impact decreases with the level of development [86–88].

Figures 1 and 2 summarize the selected criteria in the instance of QUAD nations and support the facts established in Table 6. Whereas EG and FEC have an increasing tendency, this indicates that growth in both of these variables worsens GHG emissions (Figure 1). Nevertheless, an increase in REG and TECH benefits the environment and causes a drop in GHG emissions, (Figure 2).

The findings of the Dumitrescu–Hurlin panel causality approach are shown in Table 7. Similarly, any approach that prioritizes EG, FEC, REG, and TECH would affect GHG. Furthermore, GHG have a bidirectional causal relationship with EG, FEC, REG, and TECH [63,89,90]. The table is separated into different sets of examining causality where in the first part it observed that EG causes GHG while GHG also causes EG which is not only explaining the diversity of selected country. FEC representing non-renewable energy and REG representing renewable energy both has bidirectional causation with GHG, but FEC was observed to be deteriorating factor for GHG while REG was observed to be corrective factor which helps to improve environment in QUAD countries. Similarly, TECH was also observed to have bi-directional causation, but as per the Table 6 it was observed that improvement in TECH helps the environment to improve.

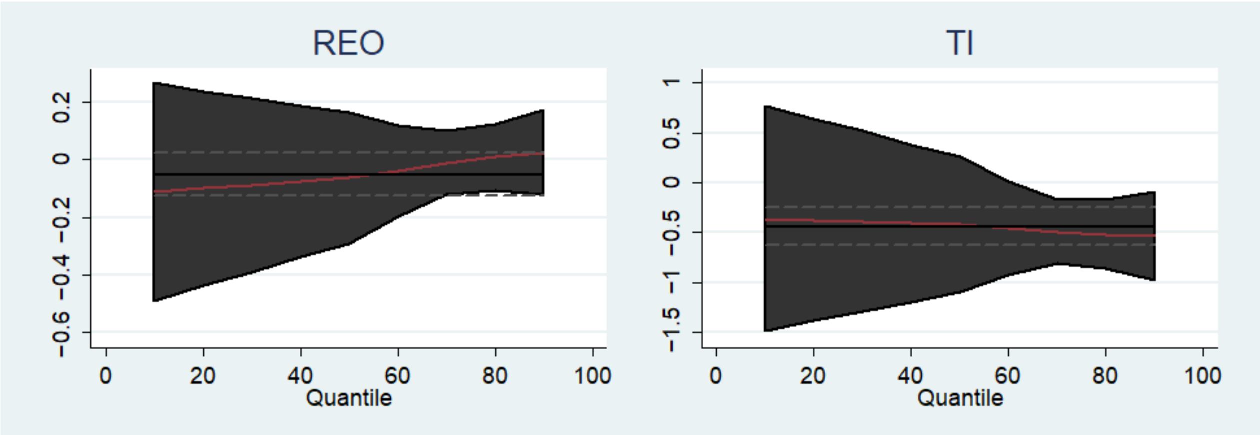

Figure 1. MMQR Graph of EG and FEC while accelerating GHG emission.

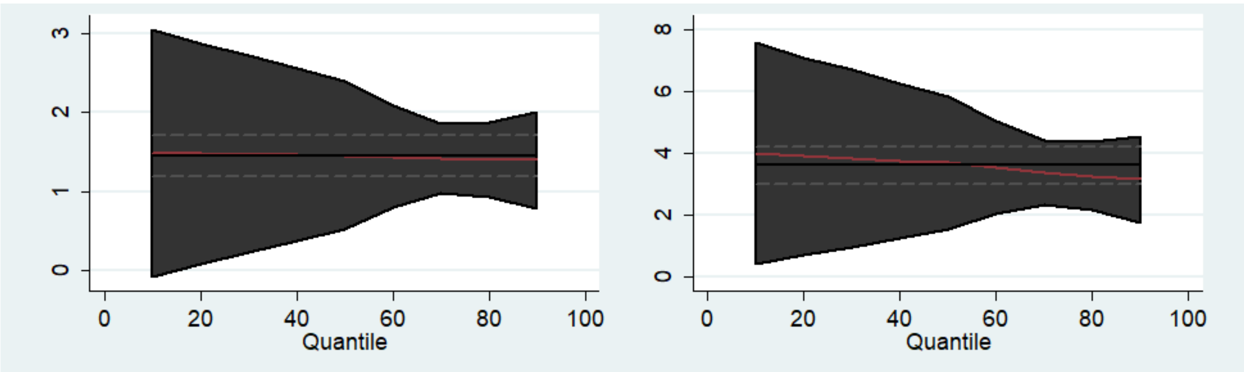

Figure 2. MMQR Graph of REG and TECH while correcting GHG emission.

Table 7. Dumitrescu-Hurlin Panel Causality Test.

H_o	$Wald_{Stats}$	$\bar{Z}_{Stats}$	*p*-Value
EG–GHG	2.69772 **	2.040	0.0413
GHG–EG	5.41761 ***	5.553	0.0000
FEC–GHG	5.05789 ***	4.214	0.000
GHG–FEC	4.66936 ***	4.586	0.000
REG–GHG	4.83730 ***	−4.803	0.000
GHG–REG	3.99679 ***	3.718	0.0002
TECH–GHG	2.57801 *	−1.885	0.0593
GHG–TECH	5.58773 ***	5.772	0.000

*** (1%), ** (5%), and * (10%).

6. Conclusions and Policy Implication

The initial purpose of this research is to apply the novel research methods for estimating the influence of energy consumption, economic growth, and technological innovation on the environment as an increase or decrease in "greenhouse gases" using evidence from QUAD economies from 1991 to 2021. This study utilizes a novel exogenous variable, i.e., "Fossil-fuel energy consumption", and renewable energy generation. To get the required outcomes, we employed recently developed econometric techniques. This research also investigates the influence of economic growth and innovation on greenhouse gases. The study employed the "Method of Moment Quantile Regression", Pesaran slope heterogeneity, panel unit root, and cross-section dependence tests, as well as the Westerlund error correction mechanism test and the Dumitrescu Hurlin panel causality test. The research evidence started with the Jarque–Bera normality test, which revealed that the data was not ordinarily distributed and that utilizing parametric results would result in biased conclusions, leading to the proposal of the MMQR. The data also indicated that the slopes and interconnectedness of cross-sections varied. The panel unit root test demonstrated the data's non-stationarity across all variables. In terms of greenhouse gases, the long-run cointegration relationship between "economic growth, fossil-fuel energy consumption, renewable energy generation, and technological innovation" has also been demonstrated.

The MMQR regression revealed that there are two types of variable, such as economic growth and fossil-fuel energy consumption, having a deteriorating impact on greenhouse gas levels and the overall environment while renewable energy generation and innovation are having a corrective impact on greenhouse gases. The magnitude of the deteriorating factors, such as economic growth and fossil-fuel energy consumption, is similar as their impact is higher in case of location-based then scale-based regression whereas renewable energy generation and technological innovation demonstrate the opposite response, as renewable energy generation is higher in the case of scale-based regression while technological innovation is higher in the case of location-based regression. In the case of quantile regression, both fossil-fuel energy consumption and economic growth are still having a deteriorating impact on greenhouse gases, which decreases at the higher quantiles than the lower ones, meaning that as the economic development of the country increases, the deteriorating impact on the greenhouse gases decreases in case of QUAD nations. Furthermore, in the case of renewable energy generation and innovation which are still having a corrective impact on greenhouse gases, again, their response is different at different quantiles, e.g., the corrective impact of renewable energy generation increases at higher quantiles while the corrective impact of innovation decreases at higher quantile. The behavior of renewable energy generation, innovation, and fossil-fuel energy consumption points towards an important outcome. With the development of QUAD nations, their dependency on fossil-fuel energy consumption decreases and renewable energy generation increases, but the investment in innovation will also have a decreasing corrective impact on greenhouse gases. Therefore, looking into these policy outcomes, every nation must tune their energy utilization policies accordingly.

Finally, the QUAD nations should expand their investment in renewable energy generation. They must spend more in renewable energy generation to fulfil the energy demands of industrialization while reducing energy-related greenhouse gases. Furthermore, policymakers should consider the asymmetric behavior of the fossil-fuel energy consumption and economic growth when developing energy, environmental, and growth-related policies. Because the conclusions of the study are confined to the QUAD nations, they cannot be extended to other countries. Similar research might be carried out for a number of other nations. Based on the study's asymmetric findings, further research might look at the nonlinear behavior of the energy, growth, and environment nexus.

According to the findings, in order to limit the impact of economic growth and fossil-fuel energy consumption on greenhouse gases, QUAD nations need to target consumption of energy, particularly industries that use more energy or are the principal source of greenhouse gases. Promoting ecologically friendly technology contributes to lower greenhouse gases. These nations utilize more of the energy, and therefore QUAD economies must aim for a balance in energy consumption and production, economic growth, and innovation to decrease the harm of greenhouse gases and promote sustainable green growth.

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