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Article

Drivers of Carbon Emissions in Turkey and Indonesia: The Roles of Energy Use, Natural Disasters, and Technological Change

Peter Oluwasegun Igunnu * and **Mumtaz Ali**

Banking and Finance Department, Economic and Business Administrative Science Faculty, Near East University, TRNC Mersin 10, 99138 Nicosia, Turkey

* Correspondence: igunnupeter@gmail.com

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Abstract: Switching to renewable energy is key to environmental resilience, especially with the growing problems of fossil fuel dependence and increasing natural disasters. This study looks into how fossil fuel consumption, natural disasters, and adoption of renewable energy technologies affect carbon dioxide (CO_2) emissions in Turkey and Indonesia. The analysis is based on the Method of Moments Quantile Regression (MMQR) approach, which captures the heterogeneous effects of these variables across different emission levels. Additionally, Feasible Generalized Least Squares (FGLS) is employed as a robustness check to validate the consistency of the results. The findings show that fossil fuel use contributes to higher CO_2 emissions, especially at the lower and middle quantiles. Natural disasters further increase emissions due to the increased energy demand for emergency response and recovery. On the other hand, the expansion of renewable energy leads to consistent and significant reductions of emissions across all levels. These results highlight the need for Turkey and Indonesia to invest in renewable energy infrastructure, implement carbon mitigation policies, integrate disaster risk management in energy planning, and promote innovation in green technologies to achieve long-term sustainability and environmental protection.

Keywords: Fossil Energy; Natural Disaster; Renewable Energy; Carbon Emissions; MMQR Approach

1. Introduction

Climate change is a critical worldwide issue, presenting substantial issues stemming from CO_2 emissions. Issues associated with elevated atmospheric CO_2 emissions encompass rising global temperatures [1], heightened frequency of climatic extremes [2], and damage to ecosystems [3]. It is imperative to address these crucial concerns, necessitating scholars, policymakers, and international organizations to prioritize sustainable energy systems, technological advances, and effective emission control regulations.

Similar to other developing nations, Turkey and Indonesia encounter distinct challenges in achieving a balance between economic advancement and environmental sustainability. This is due to the rapid urbanisation occurring in both countries, which has generated significant energy consumption and elevated CO_2 emissions. Turkey is endeavouring to diversify its fuel mix to incorporate renewable energy; yet, dependence on fossil fuels remains predominant. In 2023, coal constituted 36.2% and natural gas 21.0%, leading to fossil fuels representing around 57.2% of Turkey's energy generation sources [4,5]. Turkey has traditionally depended on fossil fuels for more than 80% of its basic energy needs [6]. By 2025, Turkey is anticipated to surpass Germany as Europe's leading emitter of fossil fuel pollutants, highlighting the environmental consequences of this dependency [6]. Similarly, Indonesia's energy sector is predominantly reliant on fossil fuels, as a significant portion of its overall energy consumption is derived from them [7]. This reliance not only exacerbates environmental degradation but also subjects the nation to transition risks in accordance with global shifts towards renewable energy sources.

Natural catastrophes can also cause both short-term and long-term increases in CO_2 emissions by damaging clean energy infrastructure and raising the demand for fossil fuels during recovery stages. Rebuilding typically depends on materials and energy sources that are heavy in carbon, especially in countries where renewable energy sources are not yet fully integrated into the grid [8,9]. Also, preparing for disasters usually focuses more on resilience than sustainability, which could accidentally lead to increased emissions during restoration.

Furthermore, the specific geographical positions of Turkey and Indonesia render them significantly susceptible to calamities. Turkey is predisposed to significant earthquakes due to its location in one of the most seismically active regions on the planet. An extreme instance is the two catastrophic earthquakes that occurred in Southern Turkey and Northwest Syria, resulting in around 16,000 fatalities [10]. Indonesia has frequent earthquakes, tsunamis, and volcanic eruptions along the Pacific "Ring of Fire." The 2004 Indian Ocean tsunami, triggered by a 9.1 magnitude earthquake near Sumatra, resulted in approximately 230,000 fatalities across multiple countries, with Indonesia experiencing the highest toll [11]. A recent earthquake in West Java Province resulted in over 300 fatalities and around 108,000 individuals rendered homeless [12]. In addition to these recurring natural disasters resulting in fatalities, they also devastate infrastructure and the economy.

The coupling of these calamities with increased expenditure on fossil fuels emphasizes the necessity for effective mitigation techniques. Transitioning from fossil fuels mitigates CO_2 emissions and enhances energy security, rendering solar, wind, and hydroelectric power feasible renewable energy alternatives. Empirical evidence indicates that, particularly in the long term, heightened utilisation of renewable energy leads to a reduction in CO_2 emissions [13,14]. This indicates that the principal avenue for environmental action is via renewable energy. Embracing renewable energy mitigates the detrimental effects of fossil fuels and aids in disaster recovery [15]. The centralised structure of conventional fossil fuel infrastructure renders it vulnerable to natural disasters, leading to prolonged power outages and economic detriment [8,16]. In the event of the disintegration of centralised systems, renewable energy sources such as solar panels and wind turbines offer critical electricity and remain operational throughout such calamities [9]. Renewable energy enhances energy resilience, facilitating a more dependable power supply before, during, and after a crisis.

The implementation of renewable energy sources must be complemented with sustainable technical advancements to effectively solve environmental issues. Technological advancement may result in enhanced energy efficiency, the formulation of sustainable manufacturing methods, and the generation of environmentally friendly products and services. The adoption of green building principles, the use of energy-efficient gadgets, and the integration of smart grid technology will reduce emissions and energy consumption [17,18]. Moreover, advancements in renewable energy technology might enhance their cost-effectiveness and efficiency, hence accelerating the shift from fossil fuels [19]. Robust early warning systems, resilient infrastructure, and sophisticated emergency response tactics can mitigate the impacts of natural catastrophes through sustainable technological innovation [20]. Advanced big data analytics and the use of artificial intelligence (AI) provide superior predictive models for catastrophes, assisting governments in implementing prompt actions to mitigate damage to vulnerable regions. Furthermore, the kernel density estimates in **Figure 1**, provides an overview of the data distributions, offering insight into the underlying patterns that shape the empirical analysis.

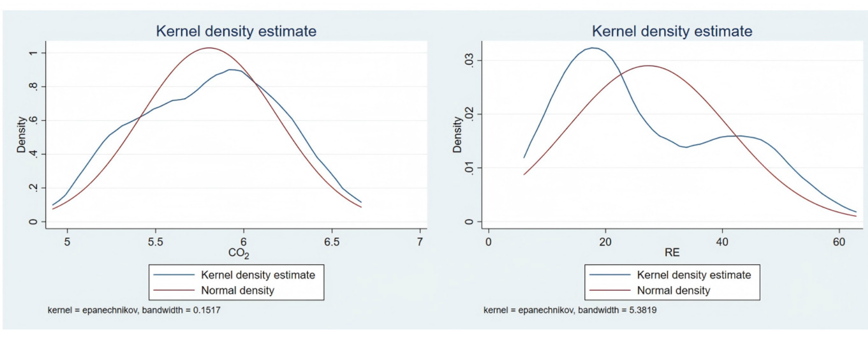

Figure 1. *Cont.*

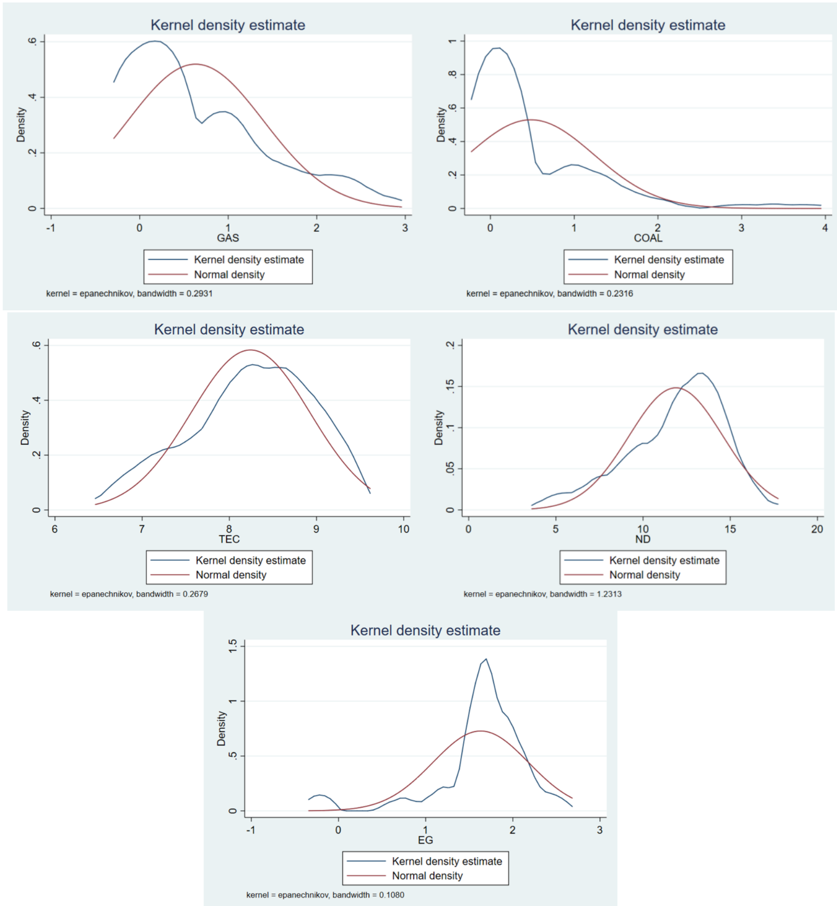

Figure 1. Kernel density graphs.

As noted in the Atlas [21], fossil fuels remain the primary source of electricity for Turkey and Indonesia, contributing over 70%. In addition, their susceptibility to climate disasters like floods and earthquakes makes achieving sustainable energy transitions more difficult. These two pressures of environmental vulnerability and carbon intensity lead to a strategic policy dilemma. However, very little is known about how these factors interact at varying levels of emissions in disaster-prone, fossil-reliant countries. This study bridges this gap, applying advanced quantile techniques to evaluate the impact of fossil and renewable energies, natural disasters, economic growth, and technological innovation on CO_2 emissions.

Furthermore, although much work has been done on the factors driving CO_2 emissions, the relationship between these factors and varying emission levels is understudied. In most cases, traditional econometric approaches do not account for the influence of fossil energy (FE), natural disasters (lnND), and renewable energy (RE) on different emissions quantiles, treating their relationships as constant.

In nations such as Turkey and Indonesia, which are not only exposed to disasters but are also among the emerging economies with the highest CO_2 emissions, the impact of natural disasters on emissions is largely overlooked [7,10]. Both nations contend with rising energy consumption, primarily fueled by swift industrial growth, and remain significantly reliant on fossil fuels, despite an ongoing transition in energy sources. These nations, along with their vulnerability to earthquakes, tsunamis, and other natural calamities, present a compelling opportunity to examine the correlation between disaster exposure, fossil fuel reliance, and emissions [22]. Turkey and Indonesia were selected as they illustrate the simultaneous challenges of energy transition and climate threats in growing economies. The results facilitate the development of national energy and climate strategies and offer pertinent insights for other economies in Southeast Asia, the Middle East, and beyond. Both nations remain significant contributors to carbon emissions, despite efforts to convert to renewable energy, underscoring the necessity for clear and well-structured regulatory frameworks.

Furthermore, additional research predominantly concentrates on either the environment or the economy, neglecting the interaction among technology advancement, energy systems, and climate shocks. The literature gap is addressed by the utilization of the MMQR estimator, which accounts for cross-sectional dependence (CSD), non-normality, heterogeneity, and outliers commonly found in macro-panel data from emerging nations [23,24]. In contrast to conventional quantile methods, MMQR provided more robust and precise estimates of emissions throughout their distribution. These enhanced estimations provide more accurate and reliable policy recommendations, hence improving the projected emissions targets. The results are shown using FGLS and contour plots to refine the emissions objectives for Turkey and Indonesia.

The study is organised as follows: Section 2 presents a synthesis of pertinent research about the determinants of CO_2 emissions. Section 3 delineates the methodological approach. Section 4 delineates the empirical findings accompanied by a discussion of the outcomes. Section 5 concludes the analysis and proposes potential avenues for future research.

2. Literature Review

2.1. Theoretical Review

This study utilizes the Energy–Environment–Growth (EEG) framework, emphasizing the interconnections among energy consumption, economic activity, and environmental factors. In Turkey and Indonesia, like in numerous other rising countries, economic growth escalates energy consumption, primarily sourced from fossil fuels, leading to CO_2 emissions unless there is substantial integration of renewables, innovation, or structural reforms.

Bekun et al. [25] employed panel quantile regressions with FGLS on the E7 economies and validated, as the EEG model posits, that economic expansion elevates emissions, while renewable energy and institutional enhancements mitigate the rise in emissions. However, their model failed to account for natural disasters, a significant error for nations such as Indonesia and Turkey. Adewuyi and Awodumi [26] likewise excluded essential elements in their analysis of the emissions–growth link by quantile regression in western and southern Africa. Their findings revealed an inverted U relationship, wherein renewable energy acted as a crucial mitigating component at elevated quantiles; nevertheless, it did not incorporate technical innovation and disaster shocks, which are essential in disaster-prone economies.

Dai et al. [27] examined the ramifications of the extensive expansion of the renewable energy sector in China concerning green growth. Their confirmation indicated that the implementation of renewable energy resources stimulated growth and diminished emissions, a conclusion that would delight ECG theorists. Their investigation remained limited to China, and there was no effort to employ quantile methods to examine places beyond the sample's average. Danish and Ulucak [28] incorporates rising nations into a broader framework by examining green growth in BRICS countries, asserting that green technologies significantly improve the ecological performance of these nations. Like the majority of the literature, they failed to evaluate disaster variables and did not employ quantile-based methods to investigate heterogeneity.

Recent research by Adedoyin et al. [29] examined transitional nations and demonstrated that economic progress results in heightened energy consumption and emissions. Their investigation employed a linear methodology, which EEG theory and pertinent literature deem restricted due to the significant influence of nonlinear and quantile-specific dynamics.

The cited studies illustrate the strengths and deficiencies in EEG-based literature: the mitigation of emissions is achievable through renewable energy sources, while economic growth yields contradictory outcomes, and the significance of technology is paramount; however, there is a lack of systematic integration of natural disaster shocks, technological advancements, and quantile level heterogeneity in the literature.

This study enhances the identified EEG frameworks by three principal additions. The initial adaptation incorporates the natural disaster variable as a metric for climatic vulnerability, hence enhancing the model's precision for nations with a high frequency of environmental shocks. The second modifies the model by recognizing technological innovation as an independent variable that both exacerbates and alleviates emissions. The final contribution elucidated the intricate, conditional linkages and interdependencies among economic growth, energy structure, disasters, and emissions, utilizing advanced quantile approaches (MMQR+FGLS). This is particularly advantageous for Turkey and Indonesia, which are swiftly advancing while encountering frequent natural disasters, necessitating a more profound and practical comprehension of emission dynamics for policy formulation.

2.2. Empirical Review

2.2.1. Carbon Emissions and Fossil Energy Nexus

Prior research has shown that fossil fuels, such as coal and gas, substantially increase global CO_2 emissions [14, 30]. The use of fossil fuels generates substantial CO_2 emissions, intensifying the urgent global challenge of climate change [31]. Furthermore, Smith, Tarui and Yamagata [32] investigated the relationship between oil prices and carbon emissions using the ARDL model and uncovered significant results. The increase in oil prices has led to elevated carbon emissions in Venezuela. In Saudi Arabia, CO_2 emissions were notably influenced by oil prices, as evidenced by an analysis utilizing the ARDL model performed by Alshehry and Belloumi [33]. Simsek and Yigit [34] investigated the relationship between oil prices and CO_2 emissions in the BRIC countries and Turkey using the Vector Autoregression testing model. Their investigation revealed that oil prices substantially influence carbon emissions in these nations. Zhao, Zhang and Wei [35] contended that a dramatic fluctuation in global oil prices might enhance investment and output in renewable energy sources, potentially leading to increased use of renewable energies.

2.2.2. Carbon Emissions and Natural Disaster Nexus

Previous studies mostly focus on the social and economic impacts of natural catastrophes, whereas their environmental effects have received scant attention. However, the detrimental impacts of natural disasters on consumption [36,37] indicate a substantial probability that these occurrences may decrease total energy consumption within an economy, ultimately leading to a reduction in CO_2 emissions. Research demonstrates that natural disasters negatively impact energy consumption [38]. Lee et al. [8] employ a panel dataset of 123 countries from 1990 to 2015, determining that natural disasters significantly adversely affect the consumption of hydrocarbon, renewable, and nuclear energy. The authors contend that natural disasters precipitate consumer impoverishment, which in turn impedes energy consumption Ogbeide-Osaretin [39]. Natural disasters may promote energy conservation by reducing motor movement and freight transportation. In contrast, other researchers have obtained conflicting outcomes. Doytch and Klein [40] establish a positive correlation between natural disasters and energy consumption, utilizing an unbalanced dataset from 80 countries between 1961 and 2011; nevertheless, this influence varies according to energy types and the economic development level of the countries. Specifically, in affluent nations with advanced technology, natural disasters that inflict infrastructural damage, such as climatic and geophysical phenomena, positively impact the utilization of renewable energy. In contrast, in medium- and low-income nations, natural disasters enhance residential and industrial energy demand, respectively.

2.2.3. Carbon Emissions and Renewable Energy Nexus

The principal objective of renewable energy investments, as noted by researchers, is to achieve CO_2 emission neutrality and improve economic stability [41]. Sustainable investments involve the allocation of financial resources towards environmental efforts, the mitigation of carbon emissions, and the management of the effects of unforeseen climate catastrophes [42]. Green and Stern [43] highlight that during the past 35 years, China's technological industry has experienced a considerable structural transition, mostly facilitated by investments in renewable energy through large-scale project financing. Investments in environmentally sustainable practices have consistently demonstrated an inverse relationship with carbon emissions. Sampath and Natarajan [44] assert that investment in renewable energy can reduce the emission of inorganic compounds into the environment. The collaborative efforts of public and private authorities in enhancing environmental quality undoubtedly provide remarkable results, as demonstrated by the outcome reported here. Yang et al. [45] assert that public-private renewable energy investment projects are a crucial solution necessary to address environmental degradation at its source. Between 2005 and 2019, Nawaz et al. [46] identified a correlation between carbon dioxide emissions and investments in renewable energy within BRICS and N-11 nations. The analysis of various renewable energy investment alternatives reveals significant fundamental relationships among population, foreign direct investments, inflation, and CO_2 emissions. Batrancea et al. [47] examined finance systems for renewable energy in the United States, Canada, and Brazil. The research findings demonstrated the substantial usefulness of renewable energy finance in reducing emissions and mitigating the adverse effects of global warming, thereby directly lessening the environmental impact of the economy in question. According to Osman et al. [48] among Malaysian Muslims, behavioural intention greatly affected the investment in renewable energy. The research findings emphasized the necessity of financing renewable energy to enhance living circumstances and reduce environmental harm. Their investigation encompassed religious attitudes, conventions, and behavioral inclinations. Research demonstrates that investment in renewable energy diminishes carbon dioxide emissions and promotes economic growth [49]. Du and Li [50] urged investments in renewable energy to promote the development of innovative, low-emission technologies that enable carbon-neutral environments.

2.2.4. Carbon Emissions and Technological Innovation Nexus

The significance of technical innovation in mitigating carbon emissions is corroborated by various research. Studies in Chinese provinces indicate that technological innovation reduces carbon emissions [51]. The advancement of technological innovation in the construction sector by BRICS nations also results in reduced carbon emissions [52]. Research on 71 nations reveals a bidirectional relationship between innovation and emissions; innovation adversely affects emissions, while emissions, conversely, positively influence innovation [53]. In China, technological advancement significantly facilitates energy conservation and diminishes carbon emissions, with energy consumption serving as a crucial mediating element. China is experiencing what is referred to as an energy consumption trap. Minimal energy usage promotes a decrease, whereas excessive energy consumption obstructs it [54]. This emphasizes the significance of technological innovation in attaining sustainable development and mitigating carbon emissions.

Industries with significant pollution, such as cement, steel, and aluminum, adopt cleaner and more efficient technologies, resulting in an overall decrease in carbon emissions due to technical advancements [55]. This alteration may occur incrementally. For example, in the MENA region, it is an inverted U shape where emissions rise with innovation and then decline after a certain threshold [56]. In some regions, like Shanghai, patent-related innovations have different impacts on emissions [57], and in RCEP countries, innovation helps reduce emissions from natural gas use [58]. Globally, there is a feedback loop: innovation reduces emissions, but rising emissions can in turn drive more innovation [53].

3. Methodology

3.1. Data

This study utilises annual data from 1991 to 2023 to examine the influence of fossil fuels (gas and coal), natural disasters, and renewable energy on carbon emissions in Turkey and Indonesia. This period was chosen due to data availability and its coverage of key transitions in energy policy, disaster frequency, and technological development in both countries. Additionally, economic development and technical innovation are incorporated into the analysis as control variables to mitigate uncertainty from excluded components. In accordance with Ali, Igunnu and Tursoy [14], we formulated the study model as follows (Equation (1)):

$$\ln CO_{2_{it}} = \phi_0 + \phi_1 FE_{it} + \phi_2 \ln ND_{it} + \phi_3 RE_{it} + \phi_4 \ln EG_{it} + \phi_5 \ln TI_{it} + \delta_{it} \quad (1)$$

$\ln CO_{2_{it}}$ is carbon emissions, FE_{it} is fossil energy, $\ln ND_{it}$ is natural disaster, RE_{it} is renewable energy, $\ln EG_{it}$ is the economic growth, and $\ln TI_{it}$ is technological innovation. ϕ_0 to ϕ_5 are the coefficients. Finally, δ_{it} represented the error term. Furthermore, **Table 1** presents extensive information regarding the research variable.

Table 1. Variable description.

Variables	Abb.	Measurement	Source
Carbon Emissions	CO_2	Carbon dioxide (CO_2) emissions (total)	
Renewable Energy	RE	Renewable energy consumption (% of total final energy consumption)	
Economic Growth	EG	GDP growth (annual %)	
Gas	FE	Natural gas rents (% of GDP)	WDI [59]
Coal		Coal rents (% of GDP)	
Technological Innovation	TEC	Patent applications, non-residents and residents	
Natural Disaster	ND	Total number of people affected by disasters	OWD [11]

3.2. Estimation Procedure

This study utilised panel data analysis to investigate the evolving impact of RE, EG, FE, HC, and TI on CO_2 in Turkey and Indonesia. This study uses econometric methodologies, including the cross-sectional dependence (CD) test, CADF and CIPS stationarity tests, Westerlund cointegration tests, and method of moment quantile regression (MMQR) analysis, to assess the influence of each variable.

3.2.1. CD-Test

The CD test is widely used in panel data analysis to identify cross-sectional dependence. These tests comprise the Pesaran-scaled LM test [60] and M. Hashem Pesaran CD test [61]. The basic Breusch-Pagan LM test allows one to discover conditional heteroscedasticity in panel data. The Pesaran-scaled LM test robustly and efficiently addresses cross-sectional dependency in an unbalanced panel. Maintaining the quality of panel data analysis calls for precise testing spanning extended times, including evaluation of cross-sectional dependence (CD). Moreover, the CD test is suitable in cases when the data contains levels (0) and (1). This study first offers the CD test, considering the notable variations between the two countries. Equation (2) is the CD test statistic that Pesaran [60] describes, the CD-test statistic is shown in Equation (2).

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\wp_{ij}\right) \longrightarrow N(0,1) \tag{2}$$

3.2.2. Unit-Root Test

Subsequently, we assessed the unit root to ascertain the stability of our framework indicators, which is essential for proceeding with the cointegration study [22]. Due to the CD issue in the dataset findings, we opt for the second-generation stationary analysis instead of the first-generation analysis, as the latter fails to address this problem [62]. Using the CIPS and CADF stationary analysis suggested by Pesaran [63], we looked into whether the roots are located within the unit circle. The equational representation of the CIPS and CADF analysis is as follows (Equation (3)):

$$CIPS(N,T) = N^{-1}\sum_{I=1}^{N} t_i(N,T) \tag{3}$$

3.2.3. Cointegration Test

The study used the cointegration methodology from Westerlund [64] to look into the relationship between the dependent and independent variables. This cointegration technique may be necessary due to the interdependence of several data pieces. According to Westerlund [64], the merger test establishes a null hypothesis (H_0) asserting the absence of cointegration among the variables, which is challenged by an alternative hypothesis positing the presence of cointegration. Westerlund [64] elaborates on the evaluation of these aggregation statistics as follows (Equation (4)):

$$WG = \frac{WG^0 - N^{1/2} M_{WG}(\mathscr{s},\ell)}{(\mathcal{V}_{WG}(\mathscr{s},\ell))^{1/2}} \rightarrow N(0,1) \tag{4}$$

3.2.4. MMQR Estimation

The MMQR econometric estimator formulated by Machado and Silva [23] is the best approach for obtaining reliable results from the CD test and cointegration test estimations. As previously mentioned, MMQR applies when CD is included in the provided data. Consequently, drawing from the research conducted by Ali, Zhao and Sinha [24,65,66], we employed MMQR to assess the relationship between RE, EG, FE, ND, TI, and CO_2 emissions. This technique effectively mitigates the challenges of endogeneity, unobserved common factors, cross-dependence, spatial heterogeneity, and non-stationarity. The quantile Equation (5) for MMQR is presented below:

$$\mathrm{Q}_{it} = \varphi_i + \vartheta_{it}\alpha + (\psi_i + Q_{it}\sigma)\, \varepsilon_{it} 0.75em \quad (5)$$

The model fixed influence and Q_{it} is represented by φ_i, and ψ_i, which denote differentiable transformations of the m vector of ϑ. The subsequent is the mathematical exposition presented as Equation (6):

$$X_c = X_c(S), c = 1, 2, 3 \ldots \ldots, m \quad (6)$$

Furthermore, in the context of quantiles, estimates are derived utilising the subsequent method using Equation (7).

$$Q_y\left(\frac{T}{\vartheta_{it}}\right) = (\varphi_i + \psi_i(p(T)) + \vartheta_{it}\alpha + Q_{it}\sigma_p(T) \quad (7)$$

ϑ_{it} denotes the vector of predictor facets in Equation (5), comprising FE, lnND, RE, lnEG and lnTI. Equation (7) delineates the conditional quantile distribution of the endogenous variable, positioned on the left side. The defining characteristic of the individual effects estimate method, relative to other LS-fixed effects techniques, is the lack of an intercept term. The variables are anticipated to be time-invariant, suggesting that the disparities among the units are presumed to remain constant. The solution is refined to compute the quantiles of the gathered data (Equation (8)).

$$min_p \sum_i \sum_t \sqsubseteq_T (Y_{it} - (\psi_i + Q_{it}\sigma_p)p) \quad (8)$$

Furthermore, we employ the FGLS estimator to provide robustness. Additionally, we employed the Shapiro–Wilk test to assess the normality of data distribution, positing the null hypothesis that the variables are normally distributed in contrast to the alternative hypothesis that they are not. Also, correlation and VIF tests are performed to ascertain the relationships among the parameters and to evaluate multicollinearity, respectively. Furthermore, **Figure 2** illustrates the methodical flow of the investigation.

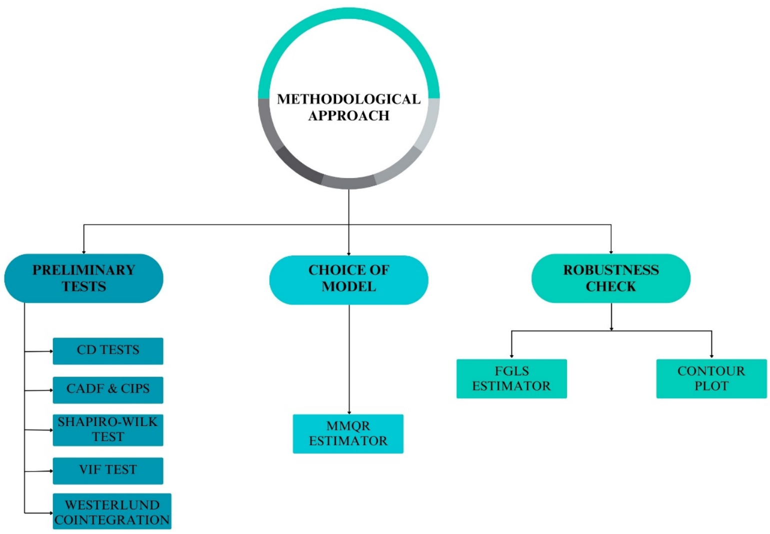

Figure 2. Methodological flow.

4. Results

The estimates of descriptive statistics are presented in **Table 2**. The average results indicate the central tendency of the examined variables, with CO_2, RE, EG, GAS, COAL, TEC, and ND having values of 5.803, 3.182, 1.631, 0.632, 0.483, 8.243, and 11.886, respectively. The dispersion values of the variables (CO_2, RE, EG, GAS, COAL, TEC, and ND) are 0.387, 0.506, 0.548, 0.768, 0.753, 0.684, and 2.687, respectively.

Table 2. Descriptive statistic estimates.

Variable	Mean	Std. Dev.	Min	Max
CO_2	5.803193	0.3872059	5.068677	6.514025
RE	3.182102	0.5057065	2.433613	4.051785
EG	1.631164	0.5482009	−0.2342979	2.57465
GAS	0.6317408	0.7683766	0.0004988	2.665158
COAL	0.4834444	0.7531237	0.0028659	3.716279
TEC	8.243187	0.6839258	6.729824	9.348449
ND	11.88615	2.687465	4.60517	16.75677

Evaluating the unit roots and CSD of the variables under investigation enables the development of empirical analysis in this study. **Table 3** displays the results of the CIPS, CADF, and CSD evaluations. The presence of CSD, as revealed in **Table 3**, compelled us to evaluate the unit root using second-generation testing methods. The outputs of CADF and CIPS indicate the existence of a mixed order unit root.

Table 3. CD and unit root estimates.

	CD-TEST		CADF		CIPS	
Variable	CD	*p*-Value	Level	1st Diff	Level	1st Diff
$lnCO_2$	5.551	0.000	−7.281		−3.476	
RE	4.874	0.000	−5.448	−2.946	−1.829	−5.888
lnND	0.632	0.527	−6.220	−3.173	−3.826	
GAS	−0.940	0.347	−7.819		−3.279	
COAL	5.119	0.000	−7.985		−2.936	
lnEG	0.735	0.462	−7.242		−6.190	
lnTI	4.362	0.000	−6.135	−4.705	−3.015	

Table 4 demonstrates the lack of multicollinearity, since all variables have VIF values under 5. The average VIF of 2.48 further confirms that multicollinearity is not a concern, hence confirming the accuracy of the regression computations.

Table 4. VIF estimates.

Variable	VIF	1/VIF
RE	4.43	0.225754
GAS	4.07	0.245745
lnTI	1.39	0.720149
lnND	1.38	0.725438
COAL	1.37	0.731568
lnEG	1.1	0.905993
Mean VIF	2.29	

Table 5 displays estimates from the Shapiro–Wilk normality test, revealing non-normality since most variables have *p*-values below 0.01. Conversely, $lnCO_2$ conforms to a normal distribution, with a *p*-value of 0.16415.

Table 5. Shapiro–Wilk estimates.

Variable	w	*p*-Value
$lnCO_2$	0.9726	0.1642
RE	0.8923	0.0000
lnND	0.8533	0.0000
GAS	0.8010	0.0000
COAL	0.6744	0.0000
lnEG	0.8220	0.0000
lnTI	0.9528	0.0158

Table 6 presents the results of the Westerlund Cointegration Test. The variance ratio statistic is 2.461, with a *p*-value of 0.0069. We dismiss the null hypothesis of no cointegration since the *p*-value is below 0.01. This indicates that there exists a long-term equilibrium relationship among the variables in the panel dataset. Additionally, **Table 7** presents the results of the correlation test.

Table 6. Westerlund cointegration.

	Statistic	*p*-Value
Variance ratio	2.461	0.0069

Table 7. Correlation test.

Variable	$lnCO_2$	RE	lnND	GAS	COAL	lnEG	lnTI
$lnCO_2$	1						
RE	−0.0805	1					
lnND	0.2233	0.4828	1				
GAS	0.128	0.8549	0.4345	1			
COAL	0.5201	0.2907	0.3069	0.2743	1		
lnEG2	−0.1808	0.0954	0.0132	−0.0136	0.0403	1	
lnTI	0.8492	0.0173	0.1761	0.1513	0.4008	−0.2351	1

MMQR Outcomes

Table 8 displays the outcomes of MMQR calculations, examining the correlation between independent variables and CO_2 emissions across several quantiles (Q1–Q5). The results demonstrate distinct effects of RE, FE (gas and coal), lnND, lnEG, and lnTI on varying levels of CO_2 emissions.

Notably, at lower quantiles, the findings indicate that fossil energy (FE), represented by gas and coal consumption, elevates CO_2 emissions. In Q1, the coefficients for gas and coal are 0.1634 and 0.0854, respectively, while in Q2, they are 0.1335 for gas and 0.0778 for coal. Both gas and coal exhibit a positive correlation with CO_2 emissions from Q1 to Q3. This indicates that a greater reliance on fossil fuels significantly elevates CO_2 emissions in low-emission environments. At elevated quantiles (Q4 and Q5), where fossil energy's contribution becomes statistically insignificant, the impact diminishes accordingly; this suggests that in high-emission economies or sectors, the marginal effect of further fossil energy use on emissions is reduced. These results complement the findings of other researchers [14,31,32], which indicate that in certain economies or sectors, transitioning from very low emissions to a moderate range significantly increases the relative elasticity of emissions concerning fossil energy consumption. Interestingly, the outcomes also indicate that gas exerts a greater marginal impact than coal at lower quantiles, suggesting that gas, commonly regarded as a cleaner transitional fuel, may significantly influence emissions in low-emission scenarios more than previously believed. This highlights the necessity of seriously re-evaluating the significance of natural gas in national energy programs focused on decarbonization. Moreover, enhancing energy efficiency, using carbon capture technologies, and utilising renewable resources may potentially reduce the excess emissions generated by fossil fuel consumption in high-emission areas.

Turkey and Indonesia remain heavily reliant on fossil fuels, especially coal, which generates a substantial portion of their electricity. Despite ongoing initiatives to diversify the energy portfolio, coal-fired power stations continue to significantly contribute to emissions in Turkey. In Indonesia, coal is the primary energy source, and the government continues to endorse coal development despite its climate obligations. The results suggest that both nations must intensify their efforts to eliminate coal and natural gas in regions with reduced CO_2 emissions. Turkey and Indonesia must accelerate the cessation of coal usage, establish carbon pricing mechanisms, and enhance investments in renewable energy infrastructure to supplant fossil fuel power plants to achieve further reductions.

The influence of lnND on CO_2 emissions varies over multiple quantiles. In the lower quantiles (Q1–Q3), lnND lacks statistical significance, indicating that in lower emission scenarios, natural disasters may not exert a direct or substantial influence on emissions. At elevated quantiles (Q4 and Q5), lnND exhibits a significant and robust positive correlation with CO_2 emissions (Q5: 0.0299, $p < 0.1$), indicating that natural disasters intensify CO_2 emissions in nations or regions with higher emission levels. This discovery corresponds with recent studies [8,40] indicating that natural disasters impair energy systems, hence augmenting dependence on fossil fuels for recovery. The reconstruction of infrastructure, rejuvenation of industry, and intensified construction efforts in the impacted areas elevate energy demand following disasters, leading to augmented emissions. Moreover, the study indicates that the environmental impact of natural catastrophes is not only immediate but also systemic, exacerbating carbon emissions in already susceptible, high-emission economies. This emphasizes the essential requirement to incorporate climate resilience and renewable energy strategies into post-disaster recovery frameworks, ensuring that reconstruction efforts do not unintentionally perpetuate carbon-intensive energy dependencies.

Turkey and Indonesia are often impacted by seismic activity, inundations, and volcanic eruptions. In Turkey, significant earthquakes have devastated the energy infrastructure, hence heightening dependence on fossil fuels during rehabilitation initiatives. In Indonesia, frequent flooding and volcanic eruptions hindered advancements in renewable energy, leading to a continued reliance on coal and diesel for electricity. The data indicate that both nations ought to incorporate resilience to natural disasters into their energy strategies to guarantee that recovery efforts, following a disaster, rely on renewable sources rather than fossil fuels.

The statistically significant coefficients from Q1 to Q4 demonstrate that renewable energy substantially decreases CO_2 emissions across all quantiles, suggesting that Indonesia and Turkey should include disaster recovery into their fossil fuel energy policies. The most significant effects manifest in the lower quantiles, Q1: −0.0276, Q2: −0.0258, whereas Q3: −0.0227 and Q4: −0.0200 exhibit a reduction at higher quantiles, while still being affected. This indicates that low-emission enterprises or economies rely significantly on renewables for carbon mitigation; however, in Q5, the effect becomes statistically negligible, suggesting that in high-emission contexts, renewable energy proves ineffectual in reducing CO_2 emissions. Furthermore, the diminishing effectiveness at higher quantiles indicates that in highly industrialized or fossil fuel-dependent areas, renewable energy must be combined with comprehensive reforms such as decommissioning high-emission infrastructure and enhancing efficiency to achieve a significant impact. This aligns with previous research [14,44] indicating that renewable energy may mitigate emissions effectively only when the energy infrastructure, energy mix, and technologies for storage and distribution are sufficiently developed.

Turkey and Indonesia are advancing in renewable energy, particularly through the utilisation of hydroelectric, solar, and wind power. The diminishing effect of renewables at elevated quantiles suggests that their utilisation is insufficient to significantly influence emission reductions in high-emission regions. Despite Turkey's significant reliance on hydropower, the nation's considerable dependency on coal-fired power plants severely constrains the effectiveness of renewable energy in mitigating emissions. Indonesia has established robust objectives to augment the proportion of renewables in its energy portfolio; yet, coal continues to be a fundamental component. This concurrently diminishes the efficacy of renewables in high-emission scenarios. Both nations must adopt more assertive measures to enhance grid integration, energy storage, and subsidies for non-carbon-intensive electricity to successfully capitalise on the potential of renewable energy. Both nations must adopt more assertive policies to enhance grid integration, energy storage, and incentives for sustainable alternatives to maximise the impact of renewable energy.

In each quantile, the correlation between lngEG and CO_2 emissions is statistically negligible, indicating that variations in economic growth do not directly or consistently influence changes in emission levels. This indicates that additional factors, such as regulatory regulations and the type or source of energy utilized, are significantly more influential in shaping emissions patterns. The insignificance of lnEG may indicate the broader structural transformations occurring in Turkey and Indonesia as they transition towards a service-oriented and knowledge-based economy. This is accompanied by enhanced energy efficiency and more stringent environmental regulations that have diminished the growth-pollution relationship [30,38]. The lngEG in the countries might be more closely linked to investments in renewable energy sources and sustainable development, hence reducing emissions often associated with economic growth.

The effect of lnTI increases from Q1 (0.2579, $p < 0.01$) to Q5 (0.3301, $p < 0.05$), indicating that lnTI exhibits a positive and statistically significant correlation with CO_2 emissions across all quantiles. This suggests that while technological advancements facilitate transformations in the energy and economic sectors, they may also correlate with increased emissions. This result supports the assertion that specific technical developments, especially in carbon-intensive industries, may result in heightened industrial activity and energy consumption, hence validating the contention that not all technological innovations are ecologically beneficial. The escalating lnTI influence over quantiles indicates that, in high-emission scenarios, technological innovation may favor industrial growth over emissions reduction.

Technological advancements in Turkey and Indonesia have primarily focused on industrial growth, infrastructural enhancement, and digital transformation, rather than explicitly targeting carbon reductions. Turkey has invested in new manufacturing and transportation, while Indonesia has focused on technological advancements in mining and energy extraction, which nevertheless produce emissions. The results emphasise the imperative for Turkey and Indonesia to prioritise investments in green technology to ensure that technological progress aligns with environmental sustainability.

Table 8. MMQR estimate.

Quantiles	GAS	COAL	lnND	RE	lnEG	lnTI
Q1	0.1634* (0.0911)	0.0854* (0.0488)	−0.0131 (0.0135)	−0.0276*** (0.0074)	0.0046 (0.0653)	0.2579*** (0.0870)
Q2	0.1335** (0.0616)	0.0778** (0.0356)	−0.0061 (0.0076)	−0.0258*** (0.0051)	0.0064 (0.0485)	0.2696*** (0.0636)
Q3	0.0843 (0.0508)	0.0653** (0.0287)	0.0052 (0.0066)	−0.0227*** (0.0042)	0.0094 (0.0390)	0.2888*** (0.0514)
Q4	0.0420 (0.0735)	0.0545 (0.0412)	0.0151 (0.0099)	−0.0200*** (0.0061)	0.0119 (0.0558)	0.3053*** (0.0737)
Q5	−0.0214 (0.1278)	0.0384 (0.0719)	0.0299* (0.0169)	−0.0160 (0.0106)	0.0158 (0.0975)	0.3301** (0.1284)

Note: *** represents 1%, ** represents 5% and * represents 10% significance level.

This study employed FGLS methodologies to corroborate the findings of the MMQR model. **Table 9** presents the FGLS results, which corroborate MMQR claims that fossil energy significantly increases emissions, whereas lnND demonstrates a positive correlation with emissions, thus affirming the environmental impact of activities associated with disasters. Moreover, renewable energy reduces CO_2 emissions. Despite being statistically modest, lnEG2 indicates a neutral impact on emissions. Moreover, lnTI demonstrates a significant positive link with emissions, indicating that current advancements remain associated with energy-intensive activities.

Table 9. FGLS robustness estimate.

Variable	Coefficient	Std. Err.	*p*-Value
GAS	0.180	0.052	0.001
COAL	0.137	0.031	0.000
lnND	0.012	0.006	0.038
RE	−0.015	0.003	0.000
lnEG2	0.016	0.038	0.668
lnTI	0.386	0.034	0.000

The contour plots in **Figure 3** provide a robustness check by visually illustrating the relationship between CO_2 emissions and the explanatory factors over multiple quantiles. The colour gradients illustrate varying levels of interactions, with distinct patterns emerging at different degrees. Non-uniform distributions have diverse effects, aligning with the MMQR findings that the impact of particular factors fluctuates with rising CO_2 emissions. This graphical confirmation corroborates the study's findings and underscores the intricacy of emission dynamics in Turkey and Indonesia.

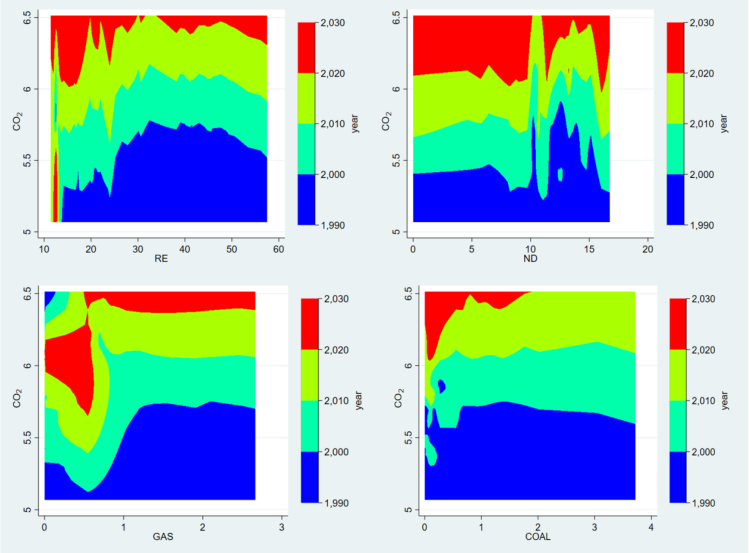

Figure 3. *Cont.*

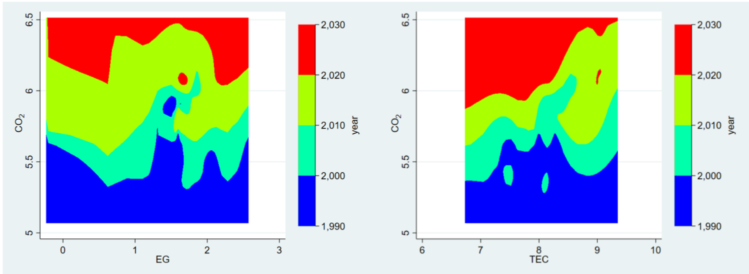

Figure 3. Contour plot outcomes.

5. Discussion

This study's findings provide significant insights into the carbon emissions of the developing nations of Indonesia and Turkey. Moreover, these data underscore the persistent dependence on fossil fuel leases, such as coal and gas, as a primary catalyst of emissions across the emissions spectrum. This outcome underscores the reliance of these nations on fossil fuels and suggests that emissions reduction strategies must initiate with a reconfiguration of the energy source composition. The policy is clear; without deliberate, significant alterations away from fossil fuels, particularly in the energy-intensive sectors of industry, electricity generation, and transportation, achieving lower emission targets will be unattainable.

Conversely, the utilization of renewable energy sources significantly and consistently decreases CO_2 emissions, particularly at elevated quantiles. This indicates that the utilization of renewable energy sources possesses the most significant capacity to mitigate emissions at elevated levels. This interpretation has dual implications. Firstly, it substantiates the fundamental principles of the Energy–Environment–Growth paradigm, which posits that the transition to clean energy improves environmental quality. Secondly, it underscores the necessity of prioritizing the advancement of renewable energy systems in regions and industries characterized by high emissions and those susceptible to climate impacts. This encompasses, for Turkey and Indonesia, the industrial and urban zones, along with the disaster-prone and seismically active areas. Consequently, authorities must not only augment the proportion of renewables but also ensure their strategic distribution in accordance with national emission profiles and catastrophe vulnerability assessments.

The insignificance of the emission and economic growth relationship across all quantiles of the emissions distribution directly contradicts the notion that economic growth results in heightened emissions. This may be attributed to the structural transformations that have recently occurred in both countries, encompassing the shift from energy-intensive production to service-oriented economies, enhancements in energy efficiency, and the implementation of green technologies.

However, this should not be construed as proof that economic expansion is inherently clean or benign. Rather, it demonstrates that the correlation between growth and emissions is predominantly influenced by policy, technological innovation, and institutional capability. The absence of a direct correlation between growth and emissions indicates potential for greater decoupling, provided that growth strategies are aligned with sustainability objectives. For Turkey and Indonesia, this entails green growth strategies centered on the advancement of low-carbon infrastructure, eco-industrial reclamation, and sustainable urban development to prevent future emissions counter growth.

Technological innovation consistently reduces emissions in higher quantiles when the ecological impact is greater. This validates the theoretical perspective that "green" innovation might induce more innovation. This innovation underscores the significance that innovation policy is not impartial. It necessitates organization and equilibrium and must be directed through appropriate public policy frameworks, including regulated and policy-modulated R&D funds, renewable technology innovation hubs, and national initiatives that amalgamate research on climate and climate policy. In rising economies susceptible to disasters, internal innovations or inventions must be resilient to external calamities. It suggests that the innovation needs to implement specific regulations and technical frameworks to sustain itself. Earthquakes, floods, and volcanic eruptions are prevalent in both studied nations.

Natural disasters exemplify a more complex and uneven framework. Although not very significant across all data segments, they tend to be more evident with elevated emissions. This may be attributed to the rise in fossil energy use following the tragedy, necessitated by power generation, rehabilitation, and logistical operations. Disasters frequently compromise the infrastructure of renewable energy, delaying the implementation of clean energy solutions. Disaster events include more than just environmental occurrences; they represent systematic shocks capable of modifying emissions patterns for diverse durations. Consequently, energy and environmental policies must be incorporated into a comprehensive catastrophe risk management framework. Alongside enhancing the resilience of energy systems to catastrophes, emergency disaster responses must be organized to sustain advancements in emissions reduction.

Collectively, the findings of this study hold significant implications for both policy and theory. From a policy perspective, they point to the importance of adopting multidimensional strategies that combine energy restructuring, innovation, and disaster preparedness into a unified decarbonization agenda. National policies must reflect the differentiated effects observed across the emissions distribution, focusing attention where emissions are highest and interventions are most effective. From a theoretical standpoint, the study contributes to the EEG literature by integrating natural disasters as a novel variable and employing quantile regression to uncover heterogeneous effects. This approach moves beyond traditional average-effect models and offers a more granular, policy-relevant understanding of emissions drivers.

6. Conclusions

This study utilizes the MMQR approach alongside FGLS and contour plots to analyze the correlation between renewable and fossil energy, natural disasters, economic growth, technological innovations, and CO_2 emissions across various quantiles. Renewable energy reduces emissions universally, whereas fossil energy, particularly in the lower and intermediate quantiles, dramatically elevates emissions. Emissions increase due to technical progress unless it is focused on environmental issues, while economic expansion appears to have less direct influence. Lower quantiles of natural catastrophes diminish emissions, whereas higher quantiles tend to increase emissions, indicating a scale-dependent effect.

This research offers emerging policymaking economies insights into the intersections of fossil fuel dependence, economic growth, and disaster risk. Indonesia and Turkey illustrate the impact of fossil fuel rent's CO_2 emissions on the reliance of quantile structures; both nations exhibit a deliberate dependence on fossil fuels that exacerbates the environmental situation. Turkey would benefit from improved policies that reduce reliance on fossil fuels. This can be implemented by reducing fossil fuel subsidies that artificially lower the price of carbon-intensive fuels, imposing carbon taxes to account for emission externalities, and enforcing stronger emission regulations on high-carbon sectors such as electricity production and heavy industry. These measures align with the findings and address the emissions-revenue relationship prevalent in conjunction with heavy industries.

The significant inverse relationship between renewable energy use and carbon emissions necessitates the enhancement of policies for renewable energy usage. Particular attention should be given to the deployment of renewable energy sources, specifically solar, wind, and hydroelectric projects, in areas characterized by elevated emission intensities. Moreover, the establishment of renewable energy facilities must be prioritized in disaster-prone regions where energy generation and resilience are critical. Practical tools such as feed-in tariffs, streamlined permitting for renewable installations, and public–private partnerships can support faster deployment. These actions are based on the study results and facilitate a shift to cleaner energy systems while remaining grounded in the evidence.

This study found technological innovation to be a crucial reason for enhanced emissions in the higher quantiles. Therefore, a strategic innovation policy is essential. The government is advised to prioritize allocating research and development funds towards ecologically sustainable technology advances, such as clean energy systems, managed smart grids, and industrial efficiency advancements. Innovation clusters and collaborations between academia and the corporate sector can create an ecosystem that integrates national technological advancement with sustainability.

Although economic growth is deemed statistically insignificant in this analysis across all quantiles, it is essential to note that this does not imply it is neutral for environmental impact. The insignificance suggests that there may not be automatic rises in emissions corresponding with economic growth, structural changes, or enhancements in efficiency. This fosters potential for green growth policies that maintain the existing decoupling trend. It is prudent to allocate capital towards the low-carbon sector and promote sustainable corporate practices. Moreover, enhancing energy efficiency, implementing ecological standards in production, and broadening training in the green sector facilitate sustained emission regulation.

The increased emissions resulting from natural disasters, together with their indirect and unpredictable effects, underscore the necessity of including disaster risk management in environmental and energy strategies. Infrastructures must be deliberately engineered to endure disasters and economically integrate with decentralized renewable energy systems to support communities during emergencies. Emergency preparedness plans must incorporate sustainable energy use and swift recovery to avert significant emissions increases following a disaster. This integration guarantees that climate adaptation and emissions reduction efforts align with the same objectives, as seen by the study's quantile-level variation.

This study theoretically incorporates natural catastrophes into the Energy-Environment-Growth (EEG) framework as a variable that influences the energy structure and emissions intensity. This integration enhances the EEG framework by including additional pertinent and adverse environmental shocks and their effects on emissions in a more vulnerable economy. Furthermore, utilizing the Method of Moments Quantile Regression (MMQR) technique, the study demonstrates that the factors influencing emissions do not have uniform effects but vary in their emission intensity. This has significant theoretical implications for policy formulation: attempting to maximize the average effect of interventions may be ineffective, necessitating a more nuanced approach to distribution.

The paper proposes policy recommendations based on the empirical findings. These recommendations are specific, sector-relevant, and aligned with both national and environmental strategy frameworks, thus delineating a viable trajectory towards low-carbon and climate-resilient economic development in Turkey, Indonesia, and other rising nations.

Limitations

Despite its numerous strengths, this study is nonetheless constrained in certain aspects. The study's focus encompasses Turkey and Indonesia, which may limit the applicability of the findings to other emerging economies. Subsequent research could involve a more extensive sample of countries, facilitating enhanced comparisons across diverse economic and environmental contexts. This research employs a quantitative methodology and utilizes secondary data to estimate the connection. Consequently, future researchers may utilize this model in geographically diverse economies to enhance the generalizability of results. Moreover, integrating qualitative methods would enrich our understanding of how policy mechanisms influence emissions outcomes on the ground. Finally, examining additional structural factors like financial market development, governance quality, and global integration could provide deeper insights into sustainable emissions management.

Author Contributions

Conceptualization, P.O.I. and M.A.; methodology, P.O.I.; software, P.O.I. and M.A.; validation, P.O.I. and M.A.; formal analysis, P.O.I.; resources, P.O.I.; data curation, P.O.I.; writing—original draft preparation, P.O.I. and M.A.; writing—review and editing, P.O.I. and M.A.; visualization, P.O.I.; supervision, M.A.

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Conflicts of Interest

The authors declare no conflict of interest.

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