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Sustainable Growth, Political Risk and Carbon Footprint: Do Energy Transition and Financial Expansion Matter?

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Abstract

Unclean energy consumption stimulates carbon footprint (*CF*) leading to increased environmental pollution. Renewable energy transition (*ETN*) can curb the *CF*; however, political risk can obstruct this process. Hence, this study analyses the connections between economic growth, *ETN* and *CF* by considering political risk and financial expansion in a panel of top 10 emitters from 1992 to 2020 using the method of moment quantile regressions (MM-QR). The results elucidate that *ETN* significantly reduces the *CF* in the top emitters. Thus, expanding the *ETN* is beneficial for reducing the *CF* and promoting sustainable development. Improving the political environment by reducing the political risk (*POLR*) helps curb the *CF*. The inverted U-shaped connection between *CF* and economic growth shows that increased growth can reduce *CF* if top emitters can continue to promote energy transition and political stability. The positive impact of financial expansion on *CF* becomes insignificant at higher quantiles. Finally, policy suggestions are discussed.

Keywords: Energy transition, sustainable development, political risk, carbon footprint, top emitters

JEL Classification: Q56, O13, P180, Q01

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1. Introduction

Climate change poses a grave threat to human survival. To combat this problem, around 120 global leaders joined hands at the COP26 to achieve various climate-related targets, such as securing net zero by 2050, limiting the global temperate rise to 1.5 degrees, taking measures to protect the natural habitats and communities, and mobilizing the necessary finance (Coleman, 2021). However, controlling global warming and acquiring environmental goals requires reducing anthropogenic emissions, which are strongly tied to the expansion in economic growth (IEA, 2023).

The targets of COP26 and the intentions to reduce emissions are well aligned with the Sustainable Development Goals (SDGs), which present various targets that can be achieved to decrease unsustainability associated with development. Since the consumption of fossil energy has heightened CO_2 generation (Kanat *et al*., 2022), the modern trend of energy transition has emerged as a potential solution to continue the pace of development along with safeguarding environmental quality (Tang *et al*., 2022). The adoption of energy sources, such as solar, wind, bioenergy, geothermal, wave, hydropower and tidal, is rapidly increasing due to their environmental benefits. The United Nations (UN) has duly acknowledged the significance of renewable energy sources within the framework of Sustainable Development Goal 7 (SDG-7). This recognition stems from the understanding that the imperative of mitigating unsustainable development patterns necessitates the harnessing of affordable and environmentally benign clean energy solutions. Additionally, replacing conventional fossil fuels with renewables can enhance the chances of developing a more effective climate control mechanism that can help to secure SDG-13.

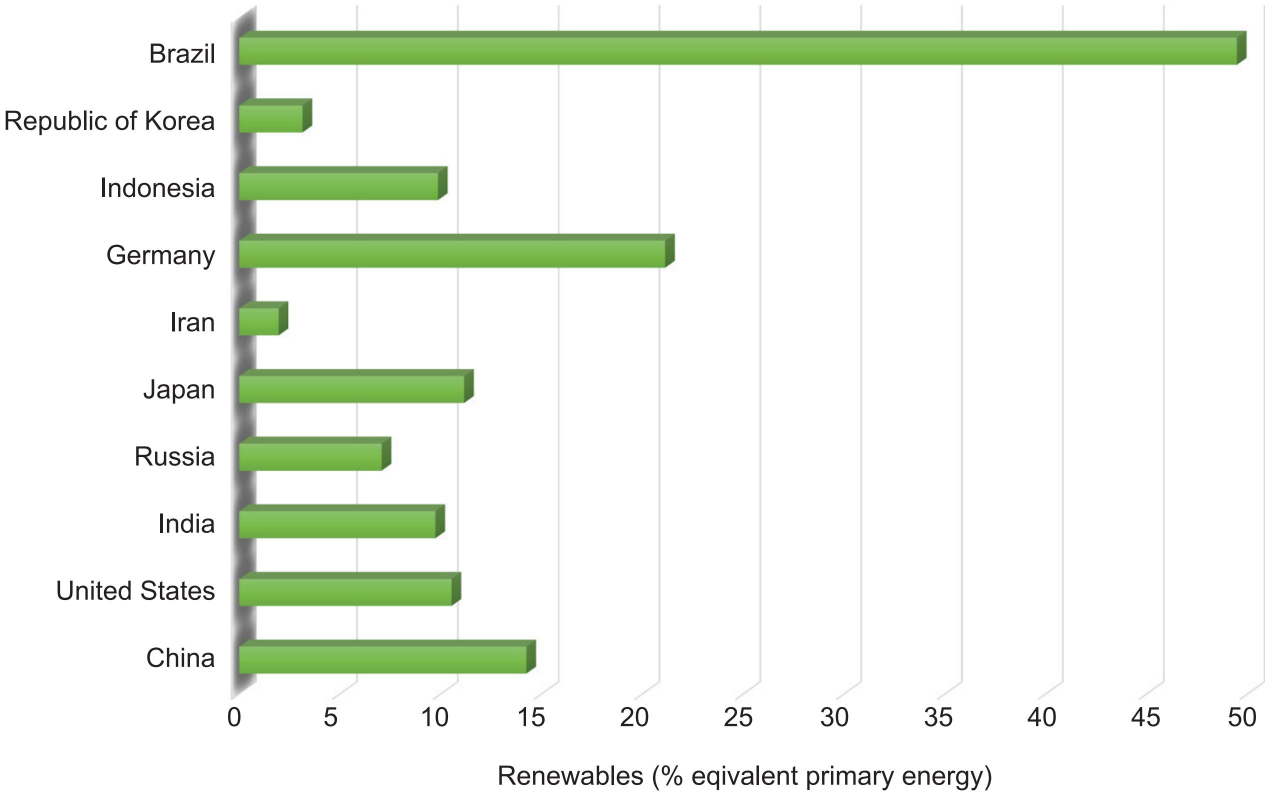
Environmental economists have engaged in extensive and ongoing debates regarding the mechanisms through which development influences environmental outcomes. In this regard, the environmental Kuznets curve (EKC) hypothesis is regarded as a framework to study the complex relationship between ecological deterioration and economic progress in the presence of various other factors that can affect development levels and ecological outcomes (Grossman and Krueger, 1995). The EKC postulates that development can have various effects on the quality of the environment due to the different features of various development stages. For instance, technique and composition effects prevalent at high levels of growth can enhance environmental protection by accelerating technological innovation and structural change (Shahbaz *et al*., 2014). Furthermore, advanced stages of development cultivate a heightened sense of environmental awareness within societies, giving rise to more favourable environmental regulations. When coupled with increased innovation and knowledge, these regulations act synergistically to expedite the widespread adoption of clean energy technologies (Dai, Ahmed *et al*., 2023). On the contrary, nations overlook the need to safeguard the environment at lower levels of growth, leading to weak environmental regulations. Thus, a scale effect holds at the early stages of development which intensifies production with adverse ecological effects (Lau *et al*., 2014). Due to these distinct characteristics of development, environmental pollution can be decreased due to higher development levels while low development can intensify emissions and environmental pollution, forming an inverse U-shaped connection (EKC) between economic development and environmental pollution.

As elucidated previously, the adoption of renewable energy sources has the potential to modify the traditionally positive relationship between environmental pollution and economic growth, thereby facilitating the emergence of the EKC association. In addition, financial expansion (*FN*) can also support technological innovation and green energy generation, which play a significant role in the EKC (Kihombo *et al*., 2021). *FN* provides efficient and reliable means of financing green projects leading to an improvement in ecological quality. In contrast, *FN* can also drive expansion in business operations, development of massive infrastructure, increases in consumption trends and energy use, which in turn can significantly boost environmental pollution (Baloch *et al*., 2020).

This study probes the interplay between energy transition, financial expansion and *CF* in the presence of political risk for sustainable growth and environmental policies. The political stability of nations can affect their development, energy transition targets, financial expansion and sustainable growth agenda. Political risks are generally based on 12 political risk components: internal conflicts, corruption, law and order, government stability, democratic accountability, religious tensions, external conflicts, socioeconomic conditions, bureaucracy quality, ethnic tensions, investment profiles, and military in politics (ICRG, 2021). These factors can likely affect the performance of businesses and the stability of environmental policy. Elevated levels of political risk can cultivate a climate conducive to poor governance practices, thereby impeding the effective enforcement and implementation of ecological regulations (Peng *et al*., 2022). Corruption and other intuitional issues can erode the efficiency of businesses, leading to more resource use. However, low political risks can promote persistent development with more efficiency and lower ecological degradation (Rizk and Slimane, 2018).

To achieve the aim of this study, this investigation focuses on the 10 highest emitting nations, namely India, China, Japan, the United States (US), Iran, the Republic of Korea, Brazil, Germany, Indonesia and Russia. With an extensive share of 68% in global CO_2 emissions (Statista, 2021), this selected country group contributes massively to global ecological degradation and climate change. Hence, carbon neutrality will remain just a dream without reducing the carbon footprint of these nations. Apart from higher carbon emissions, India, Japan, China, the US, Russia, Germany, Iran, the Republic of Korea and Brazil are categorized among the economies with the largest energy consumption (Statista, 2022). The progress in terms of renewable energy adoption in Figure 1 shows that the rate of energy transition is less than 14% in all the nations except Brazil, Germany and China. Considering that some of these nations have the largest economies with substantial energy use, rapid development, high conflicts and significant environmental pollution, it is very relevant to apprehend the interplay between *ETN*, *FN* and *CF*, accounting for the changing political risk situation in the context of sustainable growth.

Figure 1: Renewable energy transition (2020)



Source: Authors´ own elaboration

Given this background, this work probes the heterogeneous impacts of *ETN*, economic growth and *FN* on carbon footprint by considering political risk. Previous studies have not analysed the heterogeneous impacts of *ETN*, *FN* and political risk on *CF* in the 10 highest emitters; hence, this study deviates from earlier studies. This study also assesses the interplay between growth and *CF* by using the EKC concept to suggest sustainable growth strategies. Unlike the previous works, the MM-QR test is used to understand the heterogeneous impacts of *ETN*, *FN* and political risk on *CF*. This method can unfold the connections between regressors and *CF* at various quantiles and thus, the variations in the impacts of variables on *CF* can be captured. This method can tackle the spiral dependency problems along with considering variations in *CF* and selected drivers of *CF*.

2. Literature Review

Economic activities are extensively dependent on energy use (Shahbaz *et al*., 2017). In straightforward terms, energy drives development; nevertheless, energy consumption also triggers the generation of emissions, leading to adverse environmental consequences (Balsalobre *et al*., 2015). However, the negative impacts of energy are mostly related to the use of conventional energy sources, which are also known as nonrenewable (*i.e.*, gas, oil, coal). These energy sources are widely adopted by economies; thereby, environmental deterioration is rising around the world (Kanat *et al*., 2022). To address the ecological issues, the world is inclined towards adopting energy transition plans targeted at replacing conventional energy with renewables. Some research works examining the influence of the energy transition on environmental sustainability are reviewed below.

The research by Tang *et al*. (2022) showed that *ETN* and economic stability curb ecological footprint (*EF*) in BRICS while stability of government enhances *EF*. Koengkan and Fuinhas (2020) found that *ETN* helps bring down CO_2 emissions in Latin American countries. However, economic growth (*GR*) enhances the generation of emissions. The research by Afshan *et al*. (2022) unveiled that *ETN* lowers the *EF* in OECD nations. Regarding the *GR* and *EF* connection, the EKC is found. According to Ahmad, Ahmed, Riaz, *et al*. (2023), enhancing the *ETN* limits CO_2 generation in European Union (EU) nations. In addition, *GR* stimulates emission generation. In the Emerging 7 (E7) countries, Ahmad, Ahmed, Akbar, *et al*. (2023) evidenced that *ETN* has favourable environmental effects by curbing emissions while *GR* accelerates CO_2 generation. Besides these studies, the direct impacts of *ETN* on ecological sustainability are overlooked. Nevertheless, it is important to note that several studies have uncovered negative relationships between renewable energy sources and environmental pollution. For instance, Kahouli *et al*. (2022) revealed that green energy lessens environmental pollution in Saudi Arabia. Likewise, Sun *et al*. (2022) found that renewable energy mitigates pollution levels in a group of 11 nations (G11). Similarly, Akram *et al*. (2020) concluded that green energy curbs pollution levels and its effect increases with the increase in the consumption of such sources. Apart from this, various other studies have illustrated that green energy augments environmental quality (Ben Mbarek *et al*., 2018; Cheng *et al*., 2019; Danish *et al*., 2019; Destek and Aslan, 2020; Ghazouani *et al*., 2020; Paramati *et al*., 2017; Pata, 2021).

Apart from *ETN*, financial expansion is also very relevant to environmental outcomes. For instance, the research by Ntow-Gyamfi *et al*. (2020) revealed that expanding *FN* may curb CO_2 emissions; however, lower levels of *FN* can stimulate emissions in Africa. In another related study, Uddin *et al*. (2017) noticed that *FN* lessens CO_2 emissions in a panel of 27 countries. In a similar way, Majeed and Mazhar (2019) unveiled that *FN* is effective in decreasing emissions in 131 countries. Likewise, Destek and Sarkodie (2019) found a similar pattern in the context of *FN* and environmental pollution in Malaysia as well as China. Using global data, Kirikkaleli and Adebayo (2021) showed that *FN* curbs CO_2 emissions while *GR* enhances them. In the view of most of these studies, *FN* provides useful financial support to projects aiming at green energy generation, technological advancement and environmental sustainability. Thus, such beneficial effects of *FN* enhance sustainability.

However, many studies have found environmental deterioration associated with *FN*. For example, using the datasets from the Middle East and West Asia, Kihombo *et al*. (2021) showed that *FN* enhances *EF* and also that the EKC holds in the selected group of nations. Nasir *et al*. (2019) showed that *FN* enhances environmental pollution in five members of the Association of Southeast Asian Nations (ASEAN). Selecting datasets from some Belt and Road (BR) countries, Saud *et al*. (2019) observed that *FN* is connected with higher *EF* and rising ecological degradation. In another related study, Baloch *et al*. (2019) noticed similar adverse impacts of *FN* in the BR group of nations. Also, similar adverse impacts of *FN* were found by Ahmad *et al*. (2022) in various emerging economies. Using data from various emerging nations, Le and Ozturk (2020) established that *FN* enhances CO_2 emissions and that the EKC is valid. Using asymmetric methods, Ahmed *et al*. (2021) illustrated that *FN* enhances *EF* in the case of Japan. However, the EKC exists in Japan. In a recent study conducted by Fakher and Ahmed (2023), it was observed that *FN* has a detrimental effect on environmental quality. However, *FN* also contributes to environmental sustainability by fostering the positive effects of technological innovation on various environmental sustainability indicators. Research studies highlighting the adverse effects of *FN* on environmental quality posit that *FN* sustains business operations, facilitates infrastructure development and stimulates economic activities. Consequently, this heightened economic activity leads to increased resource utilization, thereby escalating pollution levels.

In conjunction with various other factors, it is imperative to take into account the political context of nations when formulating environmental policies, as political risk can significantly shape the effectiveness and outcomes of these policies. Some investigations have assessed the effects of political risk (*POLR*) on environmental pollution. For instance, in the case of ASEAN, Wang *et al*. (2023) illustrated that *POLR* is inversely related to the *EF*, and thereby, lower *POLR* supports environmental sustainability. Similarly, Peng *et al*. (2022) noticed that *POLR* stimulates the generation of green energy, which supports ecological sustainability. Similarly, Awosusi, Rjoub, *et al*. (2022) unveiled that *POLR* hampers the consumption of green energy in Vi*ETN*am. By estimating data from 11 nations, Zhang and Chiu (2020) asserted that *POLR* monotonically enhances CO_2 emissions. C. W. Su *et al*. (2021) showed that curbing *POLR* can enhance the consumption of green energy, which can have positive impacts on the environment. The study of Z. W. Su *et al*. (2021) found that improving the political environment by limiting *POLR* can decrease CO_2 emissions in Brazil. The research of Awosusi, Adebayo, *et al*. (2022) revealed that *POLR* augments *EF* in the BRICS. Thus, the political environment should be improved to boost ecological quality. Using data from Finland, Kartal *et al*. (2022) showed that *POLR* upsurges consumption-based CO_2 emissions.

The preceding literature review underscores the paucity of comprehensive examinations regarding the implications of renewable energy transition for environmental quality. Furthermore, the existing body of research addressing the nexus between *FN* and environmental quality shows inconclusive findings, encompassing both positive and negative impacts of *FN* on environmental quality. Notably, no extant studies have undertaken the task of evaluating the multifaceted impacts of *POLR*, *ETN* and *FN* on *CF* within the context of the ten preeminent contributors to CO_2 emissions, which collectively produce a substantial proportion of global CO_2 emissions. It is noteworthy that a majority of prior investigations have predominantly leaned on conventional regression methodologies. Consequently, the imperative to rigorously assess the heterogeneous effects of *POLR*, *ETN* and *FN* emerges as a pressing need, in order to provide robust and empirically substantiated policy recommendations. In line with this imperative, the present study introduces a novel dimension to the interrelationships among these variables by adopting the MM-QR test, thereby enhancing the reliability and robustness of our empirical findings.

3. Data and Methodology

The theoretical base of this study is linked with the concept of the EKC, which posits a non-linear connection (*i.e.*, inverted U-shaped link) between economic growth and environmental pollution (Grossman and Krueger, 1995; Pata, 2018). As discussed in the literature review and introduction to the study, renewable energy transition, financial expansion and political risk can also influence environmental pollution, and thus, the following model is formed by adding these explanatory variables.

$$(LCF)_{it} = \alpha_0 + \delta_1 LETN_{it} + \delta_2 LGR_{it} + \delta_3 (LGR)^2_{it} + \delta_4 LPOLR_{it} + \delta_5 LFN_{it} + \varepsilon_{it} \tag{1}$$

In Equation (1), *CF* refers to the carbon footprint (global hectares (gha) per person), and it is selected as a response variable. *GR* shows economic growth (per capita GDP, constant 2015 USD) and in line with the assertions of the EKC, the square of *GR* is included. *POLR* and *FN* indicate the political risk index and financial development index, respectively.

The *POLR* is computed by using the data for 12 components: internal conflicts, corruption, law and order, government stability, democratic accountability, religious tensions, external conflicts, socioeconomic conditions, bureaucracy quality, ethnic tensions, investment profiles, and military in politics. The *POLR* index is computed to gauge the political stability of countries. This index ranges between 0 to 100, where values from 0 to 49.9 indicate very high risk compared to a rating between 80 to 100, which indicates very low risk (ICRG, 2021). In simple words, lower risk points of this index show higher risk while higher points indicate a state of lower risk. The *FN* index rates economies in terms of access, depth and efficiency of their respective financial markets and institutions. This study selects the 10 highest emitting nations, namely India, China, Japan, the United States (US), Iran, the Republic of Korea, Brazil, Germany, Indonesia and Russia, based on the ranking of Statista (2021). Evidently, Brazil was not included in the list of the top 10 emitting nations; however, the unavailability of *ETN* data on Saudi Arabia, which is among the 10 top emitters, led to the selection of Brazil, which is ranked 12th in terms of emission generation. Notably, data for selected variables are not available for Canada, which is ranked 11th in terms of emissions generation.

Every variable is transformed into a natural logarithm form before estimating the results. The analysis period spans from 1992 to 2020 due to the unavailability of datasets for certain variables prior to 1992, particularly in the context of the highest emitting countries. Moreover, the datasets on *FN* and *ETN* are unavailable after 2020. The datasets on *POLR* and *GR* are downloaded from PRS Group (2023) and WB (2023), respectively. The datasets on *FN*, *ETN* and *CF* are collected from IMF (2023), OWD (2023) and GFN (2023), respectively.

3.1 Econometric methodology

In the first stage of the analysis, dealing with the descriptive statistics, the basic features of the data are explored. In addition, the Jarque–Bera test is utilized to learn about the nature of data distribution. The evidence shows that every variable selected for the analysis has an atypical distribution. Evidently, the normal regression methods are suitable when the datasets have a normal distribution, which is not the case in this study.

After this, the presence or absence of multicollinearity is checked by using the variance inflation factor (VIF). In this context, the evidence shows the absence of multicollinearity. Afterwards, considering the involvement of selected nations in mutual trade, the cross-sectional dependence (CD) analysis is also performed by using the CD, LM and scaled LM tests. The popular CD test of Pesaran (2004) is based on the following equation:

$$Pcd = \sqrt{\frac{2T}{Y(Y-1)}}\left(\sum_{i=1}^{Y-1}\sum_{j=i+1}^{Y}\hat{W}_{ij}\right) \quad (2)$$

where *Pcd* denotes the CD test, *T* depicts the analysed period, *Y* shows sample size and $\hat{W}_{ij}$ symbolizes pair-wise correlation. The application of these tests revealed CD in *CF*, *ETN*, *GR*, *POLR* and *FN*.

Proceeding to the next step, a test proposed by Pesaran and Yamagata (2008) is adopted to probe the slope homogeneity. This methodology is based on $\tilde{\Delta}$ and adjusted $\tilde{\Delta}$ methods. The adjusted $\tilde{\Delta}$ can be articulated as follows:

$$\tilde{\Delta}_{ajd} = (n)^{\frac{1}{2}} \left(\frac{2k(t-k-1}{t+1} \right)^{-\frac{1}{2}} \left(\frac{1}{n} \tilde{s} - k \right) \quad (3)$$

In addition, the $\tilde{\Delta}$ test can be written as follows:

$$\tilde{\Delta} = (n)^{\frac{1}{2}} (2k)^{-\frac{1}{2}} \left(\frac{1}{n} \tilde{s} - k \right) \quad (4)$$

The homogeneity of slope entails insignificant values of both these statistics. However, in this study, the output from these tests establishes heterogeneity of slope.

After that, it is also apposite to probe the integration levels of *CF*, *ETN*, *GR*, *POLR* and *FN*. To do so, the famous cross-sectional IPS & ADF (CIPS & CADF) approaches are chosen which are recommended by Pesaran (2007) for reliable unit root analysis, particularly in a situation of CD and heterogeneity. Unlike the first-generation tests, these advanced techniques can trace correct stationary levels in panel datasets. The equation for the CADF test can be written as follows:

$$\Delta R_{it} = \alpha_i + \vartheta_i R_{it-1} + \vartheta_i \overline{A}_{t-1} + \sum_{j=0}^{p} \vartheta_{ij} \Delta \overline{R}_{it-1} + \sum_{j=0}^{p} \vartheta_{ij} \Delta R_{it-1} + \varepsilon_{it} \quad (5)$$

where α depicts intercept, R denotes an estimated variable, p represents lag length, $\overline{A}_{t-1}$ & $\Delta \overline{R}_{it-1}$ describes the average of cross-sections, and ε denotes the error term. In this test, the significance of even one individual rejects the null hypothesis. The CIPS test is also related to this test since the average obtained from Equation (5) is needed to compute the results of the CIPS test, which is presented below:

$$CiPs_{ps} = \frac{1}{N} \sum_{i=1}^{N} agCDF_i \quad (6)$$

In Equation (6), the $CiPs_{ps}$ symbolizes the CIPS technique while *agCDF* depicts the CADF average.

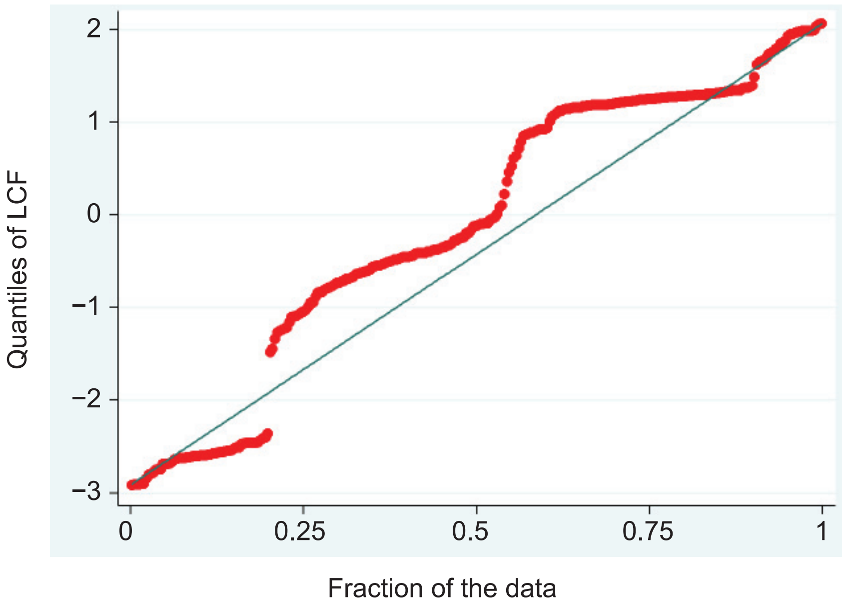
Afterwards, the Pedroni (1999) procedure is followed to check the cointegration. This test uses various within and between-dimension tests and all these tests take residuals from the equation articulated below:

$$Y_{it} = \delta_i + \vartheta_i t + \sum_{j=1}^{n} \vartheta_{ji} R_{jit} + \varepsilon_{it} \quad (7)$$

where ϑ_i denotes trend, δ is the intercept, R denotes regressors, j depicts cross-sections, Y represents the response variable (CF), t shows time, and ε_{it} is the error term. This test resolves the issues of heterogeneity but its performance can suffer due to the dependence issue in panel data.

As the datasets taken from the panel of the ten highest emitting nations have CD and heterogeneity concerns, the procedure suggested by Westerlund (2007) is also followed to probe the cointegration. This test for cointegration analysis uses four statistics, including two group and two panel statistics. Significance of at least two statistics indicates the presence of a long-run equilibrium association. In order to obtain robust p-values, the bootstrapping process is utilized based on 400 replications. The decisions of this test are considered to be reliable during dependence and heterogeneity in panels.

Figure 2: Quantile distribution of carbon footprint (gha per person)



Source: Authors´ own elaboration

As the dataset used in the study shows atypical distribution along with heterogeneity, the conventional regression tests will not be suitable to estimate these data. In addition, the carbon footprint indicates heterogeneous and distributional behaviour in Figure 2. In such a situation, the MM-QR approach is applied which was developed by Machado and Santos Silva (2019). The fixed-effect MM-QR performs well in analysing data with atypical distribution. The MM-QR methodology estimates the results of quantiles using the conditional scale function and conditional mean. This test has the ability to consider the distributional and heterogeneous nature of data and analyse the response variable at different distributional points. Thus, the use of MM-QR will provide more insights into the *FN*, *ETN*, *GR*, *POLR* and *CF* associations.

In the robustness analysis, first, the Driscoll-Kraay (DK) regression is applied. This test can handle the issue of CD. Also, this test is applicable to unbalanced and balanced panels. This test provides some important advantages, such as countering serial correlation and heteroscedasticity issues. During the application of this test, the random effect procedure based on GLS can be used to take care of heterogeneity concerns. Afterwards, the dynamic ordinary least squares (DOLS) estimation procedure is also utilized. This approach is useful in many panel data problems, such as autocorrelation, endogeneity, small sample bias and fractional integration (Dai, Alvarado *et al*., 2023). According to Dogan and Seker (2016), DOLS generates trustworthy results even with CD concerns.

4. Results and Discussion

In Table 1, the descriptive statistics of *CF*, *ETN*, *GR*, *POLR* and *FN* are presented. Although the *CF* is in per capita form, it shows significant variations indicated by the minimum and maximum values of 0.054 and 7.853, respectively. Also, the standard deviation of the *CF* is more than 2. The *ETN* ranges between 0.312 to 49.472, showing high variations in the energy transition levels of the sample nations. Similarly, variations are indicated by the minimum and maximum values of *POLR* and *GR* along with high standard deviations. The trends of economic growth (*GR*) are also plotted in Figure 3 for the sample nations. Interestingly, *CF*, *ETN*, *GR*, *POLR* and *FN* do not show normal distribution since the *p*-values of Jarque–Bera are zero for every variable.

Table 1: Descriptive statistics

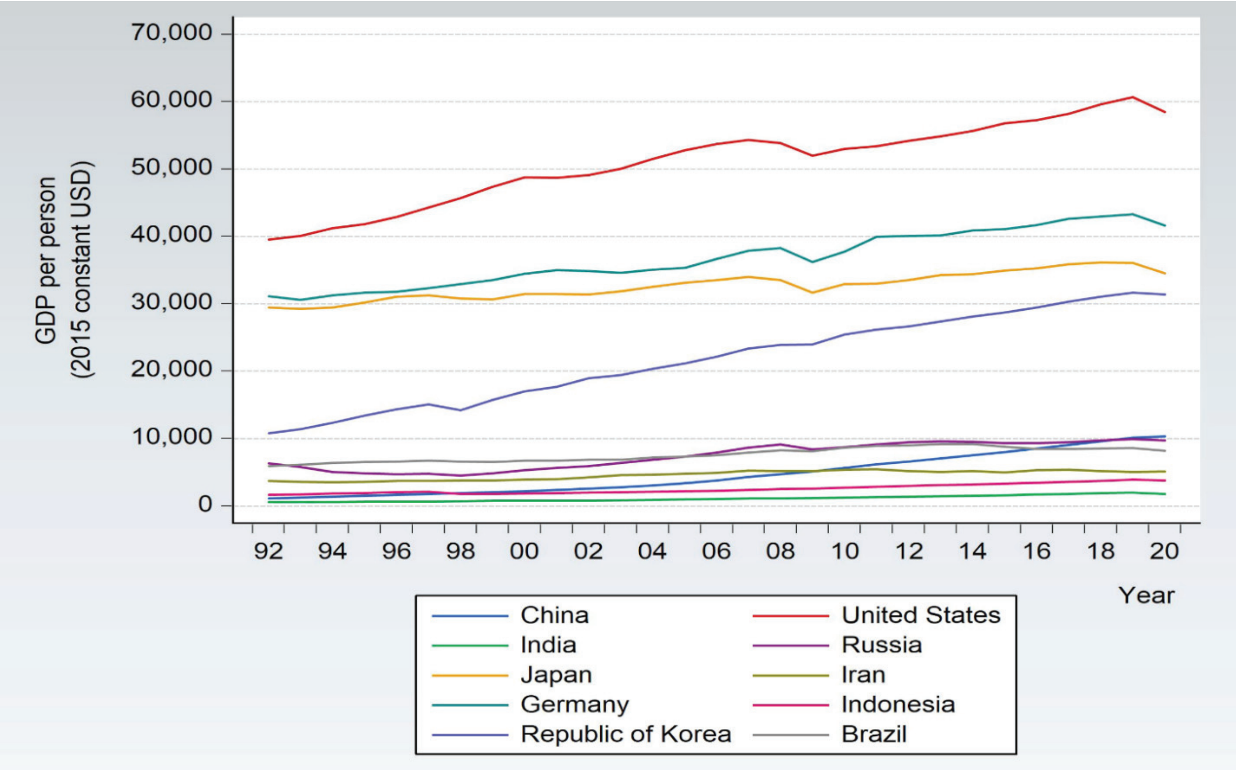
	CF	*ETN*	*GR*	*POLR*	*FN*
Mean	2.039	9.124	17019.50	69.104	0.559
Median	0.888	5.582	8306.486	66.500	0.523
Maximum	7.853	49.472	60698.01	90.000	0.925
Minimum	0.054	0.312	546.441	42.000	0.217
Standard dev.	2.059	11.931	16988.57	11.212	0.207
Jarque–Bera	46.247*	475.415*	41.486*	13.998*	21.065*
Prob.	0.000	0.000	0.000	0.001	0.000

Notes: Total observations: 290, countries: 10, period: 1992–2020; * denotes a 1% significance level.

Source: Authors´ own elaboration

These panel data, characterized by an atypical distribution and notable heterogeneities, necessitate the application of quantile-based modelling techniques to ensure the reliability and validity of the research findings. However, some more tests are conducted to have a more detailed understanding of the nature of the data. In this regard, the VIF output in Table 2 rejected the chances of multicollinearity since the values of VIF are well below 5.

Figure 3: Economic growth trends



Source: Authors´ own elaboration

Table 2: VIF results

	VIF	1/VIF
LGR	4.06	0.247
LFN	3.74	0.268
LPOLR	2.93	0.342
LETN	1.04	0.963
Mean VIF	2.94	

Source: Author´s own elaboration

Afterwards, the heterogeneity of slope is confirmed since the quantile-based modelling is suitable for heterogeneous panels. Accordingly, the Pesaran and Yamagata (2008) test is applied in Table 3. The findings on both statistics (delta and adj. delta) indicate significance, showing that the dataset of the 10 highest emitters has a heterogenous slope.

Table 3: Homogeneity of slope test

Test name	Stat.	*p*-value
$\tilde{\Delta}$	12.909*	0.000
$\tilde{\Delta}_{adjusted}$	14.821*	0.000

Note: * denotes 1% significance level.

Source: Authors´ own elaboration

Proceeding to the next stage of the analysis, the possible dependence in the panel of the 10 largest emitters is checked by using CD, LM and scaled LM tests. The evidence obtained from these tests, and shown in Table 4, shows that *ETN* and *POLR* have CD. In addition, *CF*, *GR* and *FN* also show dependence, which means that the investigation in the next step must rely on methods robust to CD.

Table 4: Tests for checking CD

	Breusch–Pagan LM	Pesaran CD	Pesaran scaled LM
LCF	460.622* [0.000]	2.459** [0.014]	43.810* [0.000]
LETN	383.153* [0.000]	13.085* [0.000]	35.6444* [0.000]
LGR	1126.94* [0.000]	33.538* [0.000]	114.046* [0.000]
LPOLR	78.159* [0.000]	3.078* [0.002]	3.495* [0.000]
LFN	636.769* [0.000]	24.465* [0.000]	62.378* [0.000]

Note: * and ** show 1% and 5% significance levels.

Source: Authors´ own elaboration

Considering the previous outcomes, the analysis of unit roots in Table 5 is performed by using two methods robust to CD and heterogeneity. The output from these techniques shows that *CF*, *ETN*, *GR*, *POLR* and *FN* are nonstationary. However, when the first difference of these variables is taken, they show stationarity. Nevertheless, the *POLR* indicates a stationary nature in the CIPS test only.

Table 5: Unit root investigation

	CADF		CIPS	
	I(1)	Δ	I(1)	Δ
LCF	−2.435	−3.232*	−2.689	−4.814*
LETN	−1.945	−4.033*	−2.471	−5.697*
LGR	−2.562	−2.768***	−2.603	−3.341*
LPOLR	−2.353	−4.422*	−3.475*	−6.089*
LFN	−2.412	−3.281*	−2.135	−4.969*

Note: CVs = −2.860 (5%), −3.100 (1%), and −2.73 (10%); *** and * show 10% and 1% significance levels.
Source: Authors´ own elaboration

Next, the Pedroni method is chosen to check the cointegration in the model in Table 6. In the results, the *p*-values of four tests (panel and group PP and AD) indicate significance. As the total tests are seven, we can say that cointegration in the model is shown by the majority of tests. This fulfils the requirement to reject the null hypothesis, thereby concluding the cointegration relationship.

Table 6: Pedroni test for cointegration

Within-dimension

	Stat.	*p*-value	Weighted stat.	*p*-value
Panel v-stat	−0.332	0.630	−2.562	0.995
Panel rho-stat	1.584	0.943	2.432	0.993
Panel PP-stat	−4.185*	0.000	−5.651*	0.000
Panel ADF-stat.	−5.071*	0.000	−5.516*	0.000

Between-dimension

	Stat.	*p*-value
Group rho-stat	3.236	0.999
Group PP-stat	−4.341*	0.000
Group ADF-stat	−3.904*	0.000

Note: * shows 1% significance level. Both trend and intercept are included.
Source: Authors´ own elaboration

As the Pedroni test is not very effective in the context of panels exhibiting CD, the popular Westerlund (2007) methodology is also applied (Table 7) to substantiate the cointegration. In this regard, the significance values of P_t and G_t statistics, based on the robust *p*-value acquired from the bootstrapped process, indicate that the selected model has cointegration.

Table 7: Westerlund (2007) test

	Value	*Z*-value	Robust *p*-value
G_t	–3.665**	–2.233	0.030
G_a	–10.391	3.043	0.223
P_t	–12.917*	–4.125	0.003
P_a	–10.703	1.745	0.145

Note: 400 replications are used for bootstrapping. ** and * show 5% and 1% significance levels.

Source: Authors´ own elaboration

After doing all the basic analyses, the MM-QR method is applied, and the findings are presented in Table 8. The output shows that *ETN* reduces the *CF* in the highest emitters. Moreover, this reduction slightly upsurges from quantile 0.5 to quantile 0.95. This evidence underscores the importance of promoting the transition to renewable energy as a crucial factor in reducing carbon footprint and improving environmental quality. By curbing fossil fuel combustion and fostering sustainable growth through the utilization of clean energy, *ETN* effectively mitigates environmental issues, leading to an overall enhancement in environmental quality. This conclusion conforms to the claims of Tang *et al*. (2022) for BRICS, Afshan *et al*. (2022) for OECD, Koengkan and Fuinhas (2020) for Latin America, and Ahmad, Ahmed, Riaz, *et al*. (2023) for EU countries.

Regarding the effects of economic growth, *GR* enhances the *CF*, explicating that development in the highest emitters enhances carbon footprint. This indicates that intensifying the economic output enhances waste generation and energy consumption, which raises the carbon footprint in the highest emitters, since these nations largely depend on the use of oil, gas and coal, and the energy transition levels are very limited in these nations. However, in accordance with the EKC concept, substantial development can markedly contribute to pollution reduction through the technique and composition effects. These effects promote the adoption of efficient technology, the enactment of pro-environmental laws, energy transition initiatives and significant structural changes, collectively leading to pollution mitigation (Shahbaz *et al*., 2014). Notably, the effect of *GR* in reducing *CF* at a higher level is exhibited from the negative coefficients of GR^2, which are highly significant in the MM-QR results. Moreover, these negative (positive) coefficients of GR^2 (*GR*) depict the presence of the EKC in the 10 highest emitters. This finding shows that the highest emitters should pursue development to offset the negative environmental influence of growth, and in this regard, they should pay attention to *ETN*. This verdict conforms to the results of some earlier studies, for example, Le and Ozturk (2020) for emerging nations, Sinha and Shahbaz (2018) for India, Ulucak and Bilgili (2018) for different income groups, Usman *et al*. (2019) for India, and Suki *et al*. (2022) for Malaysia. Although some previous investigations have revealed the EKC in different nations, this study makes it clear that including *ETN* and *POLR* is important to acquire the desired effects of *GR* on *CF*.

In the context of *POLR*, the quantile results indicate that *POLR* has a negative connection with the *CF*. Since the *POLR* index shows more risk at lower levels, this connection portrays that improving the political situation and promoting political stability with less risk can reduce the *CF*. However, the significant effect of *POLR* is only visible at quantiles 0.5 and 0.75. Furthermore, the magnitude of this impact considerably increases from quantiles 0.05 to 0.95. This empirical connection shows that more improvements in *POLR* bring greater reduction in the *CF*. This is because curbing the *POLR* can improve the political environment and reduce political uncertainty, which can help governments continue their long-run energy transition and environmental sustainability plans. Also, this stability supports the possible environmental concerns and preferences of organizations helping them continue the implementation of alternative energy solutions. Thus, reducing the *POLR* can curb *CF* and promote sustainability in economic activities, which in turn can limit climate change and global warming. This output is consistent with the outcomes of Wang *et al*. (2023) for the ASEAN, Zhang and Chiu (2020) for 11 nations, Z. W. Su *et al*. (2021) for Brazil, and Awosusi, Adebayo, *et al*. (2022) for BRICS. However, those studies used other measures of environmental degradation, and they did not reveal the effects of *POLR* at various quantiles.

Table 8: MM-QR regression results

Dependent variable = *LCF*					
Variables	$Q_{0.05}$	$Q_{0.25}$	$Q_{0.5}$	$Q_{0.75}$	$Q_{0.95}$
LETN	−0.089** [−2.46]	−0.092* [−4.66]	−0.094* [−7.22]	−0.095* [−6.23]	−0.097* [−3.95]
LGR	3.223* [7.17]	3.115* [12.74]	3.038* [18.83]	2.982* [15.72]	2.909* [9.54]
LGR2	−0.165* [−5.87]	−0.158* [−10.29]	−0.152* [−15.04]	−0.148* [−12.45]	−0.143* [−7.47]
LPOLR	−0.061 [−0.26]	−0.129 [−1.01]	−0.177** [−2.09]	−0.212** [−2.13]	−0.257 [−1.61]
LFN	0.214 [1.50]	0.146*** [1.89]	0.099*** [1.92]	0.064 [1.06]	0.018 [0.19]

Note: ***, **, and * show 10%, 5%, and 1% significance levels. *Z*-values are in brackets.

Source: Authors´ own elaboration

Finally, *FN* and *CF* show a positive connection which is only significant at quantiles 0.25 and 0.5. Moreover, this effect decreases from quantile 0.25 to quantile 0.95 and becomes insignificant after quantile 0.5. This implies that although *FN* has some adverse influences on environmental quality, enhancing the levels of *FN* makes this effect insignificant and lower in magnitude. Nevertheless, this positive connection opposes the results of Ntow-Gyamfi *et al*. (2020) for Africa, Majeed and Mazhar (2019) for 131 nations, and Kirikkaleli and Adebayo (2021) for a global dataset. However, increased lending of financial institutions can enhance business operations, accelerate infrastructure development and upsurge consumption and production, which can expand the carbon footprint. In this context, this result is consistent with the verdicts of Saud *et al*. (2019), who found that *FN* enhances *EF* in BR nations, Le and Ozturk (2020), who revealed that *FN* enhances CO_2 emissions in emerging nations, and Nasir *et al*. (2019), who established that *FN* enhances environmental pollution in ASEAN-5. The plots of MM-QR are shown in Figure 4.

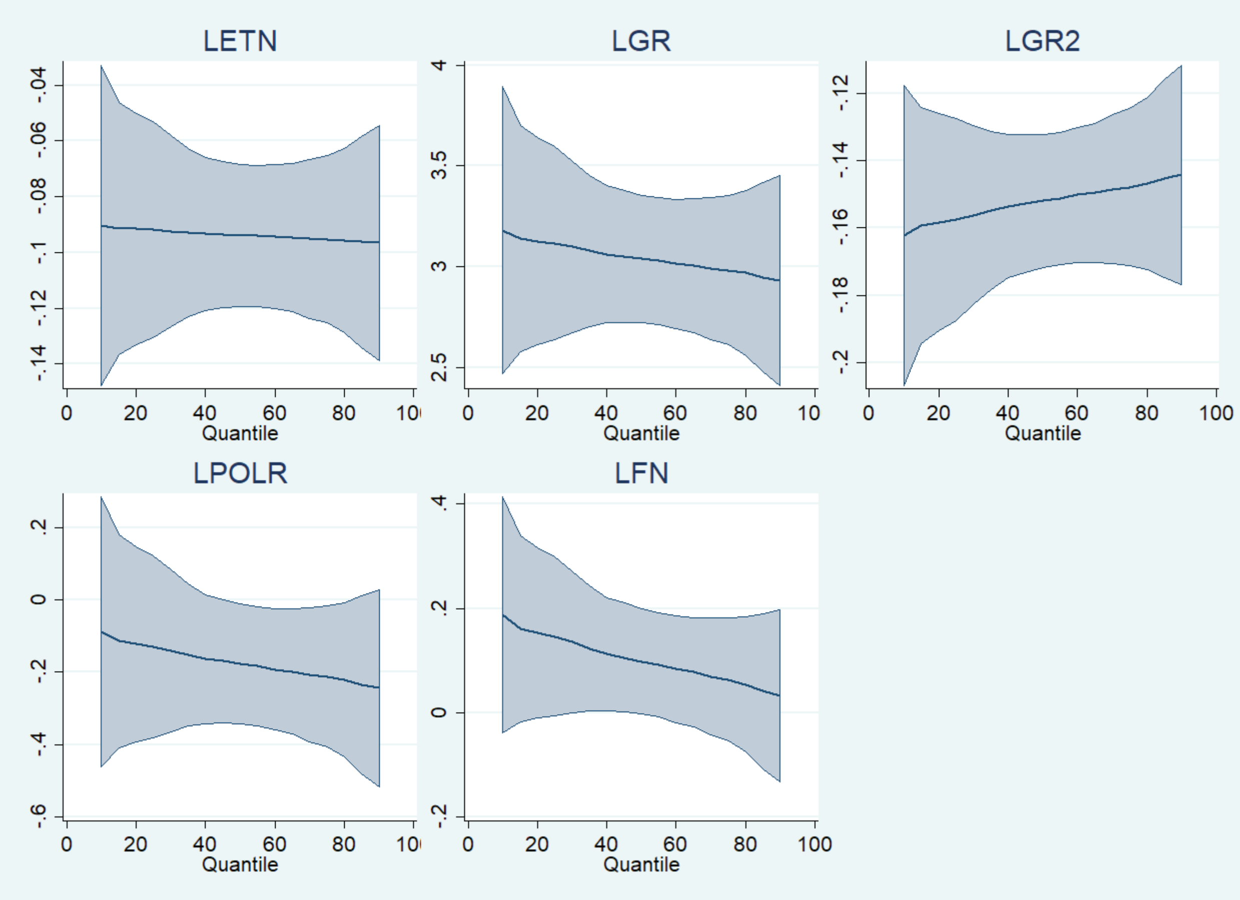
Table 9: Robustness check

	Driscoll-Kraay (DK) regression			DOLS		
Variables	**Coef.**	**Std. err.**	***t*-values**	**Coef.**	**Std. err.**	***t*-values**
LETN	–0.093*	0.023	–4.03	–0.077*	0.028	–2.772
LGR	3.039*	0.184	16.53	2.979*	0.624	4.776
LGR2	–0.152*	0.011	–13.34	–0.158*	0.036	–4.428
LPOLR	–0.168**	0.070	–2.40	–0.251**	0.125	–2.013
LFN	0.105	0.090	1.17	0.097	0.081	1.202
Cons	–13.997*	0.970	–14.43	–	–	–

Note: DK regression estimated using the random-effects GLS procedure. ** and * show 5% and 1% significance.
Source: Authors´ own elaboration

The consistency of these outcomes is validated by using the DK regression in Table 9. The use of this method shows that *ETN* curbs the *CF* while reduced *POLR* limits the *CF*. The EKC between the *CF* and GR is proved true. However, financial expansion has no significant effect on *CF*. After this, the DOLS test is also applied, which is a useful method to reveal the long-run connections. This method (Table 9) also depicts that *FN* is insignificant in the panel of highest emitters while the effects of other regressors are also consistent with the estimates generated from other tests.

Figure 4: Plots of MM-QR



Source: Authors´ own elaboration

5. Conclusion and Policy Recommendations

The analysis conducted using the MM-QR, DK regression and DOLS methodologies has yielded useful outcomes. It is evident that augmenting the process of *ETN* can yield discernible environmental advantages by promoting a reduction in *CF* within the top emission-contributing nations. Furthermore, the mitigation of *POLR* demonstrates a similarly salient potential to diminish *CF*. Notably, the findings also underscore that both promotion of *ETN* and restraint of *POLR* hold the promise of fostering carbon footprint reduction by engendering an EKC relationship between economic growth and *CF*. Thus, accelerating the growth of the economy will stimulate carbon footprint reduction at a higher level of growth. Moreover, the adverse impacts of financial expansion on environmental quality are found only at quantiles 0.25 and 0.5, and the impact of financial expansion becomes insignificant at higher quantiles.

This empirical evidence can serve as a valuable resource for policymakers in addressing the issues of sustainability and carbon footprint reduction within the top emission-contributing nations. The observed benefits of *ETN* in reducing the *CF* among the ten largest emitters offer a compelling rationale for the formulation and implementation of diverse and tailored energy transition strategies by policymakers. For example, enhancing carbon taxes, raising prices of fossil energy and fostering production of renewables can reduce the use of unclean energy and support *ETN*. Various financial support programmes can be launched to support the adoption of clean energy, such as low-interest or interest-free loans for producing and adopting renewable energy, and low taxes and duties on the import of cleaner technologies. These policies can raise the share of clean energy, which in turn can promote sustainable development because conventional energy used in economic activities can be replaced with clean energy.

In addition to this, it is also necessary to reduce *POLR*. To do this, the sample nations can work on promoting democratic principles and avoiding sudden changes in policies. Efforts to reduce corruption, respect the rule of law and foster conflict resolution processes can be vital in reducing the *POLR* and enhancing political stability. In addition, bureaucratic procedures should be simplified and governance should be improved. The energy transition and environmental policies should be stable with less political uncertainty and the political system should be based on democratic values and a smooth transition of power.

While this study yields valuable insights based on data from the top 10 emitters, it is pertinent to acknowledge its limitation in terms of sample size. Future research endeavours can enrich our understanding by broadening the scope of analysis to include additional nations that exert substantial influence on global CO_2 emissions. Such an expansion in the sample size would likely enhance the generalizability and comprehensiveness of findings in this domain. Future studies can also consider a segregated analysis of various components of political risk to provide more detailed findings. Apart from this, the present research utilizes carbon footprint to understand the effects of selected variables on environmental quality and sheds light on the possible roles of these variables in sustainable development. Future research studies may consider using more specific measures of sustainable development to directly estimate the impacts of these regressors on sustainable development.

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