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STRIVING FOR CARBON NEUTRALITY IN EU REGION: EXAMINING THE ROLE OF ENVIRONMENTAL POLICY STRINGENCY IN GEOPOLITICAL RISK AND ENERGY TRANSITION

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Abstract. Global economic policymakers are facing increasing demands from diverse environmental constituents to prioritize sustainable development through the implementation of strict environmental policies, energy transition strategies, and the reduction of fossil fuel consumption by fostering technological advancement. This study aims to assess the moderating role of environmental Policy Stringency (EPS), among Geopolitical Risks (GPR), Energy Transition (ET), Technological Innovation (INV), and environmental degradation (CO_2 emission). This study relies on empirical datasets spanning the years 1990 to 2022 in 13 EU countries and employed an extensive range of econometric techniques., Dynamic Ordinary Least Square (DOLS), Fully modified Ordinary Least Square (FMOLS), Canonical Cointegration Regression (CCR), and Method of Moment Quantile Regression (MMQR) to examine the data. The empirical findings demonstrate that interaction of GPR*EPS, INV*EPS, and ET*EPS plays a crucial role in promoting environmental sustainability and lowering CO_2 emissions. Whereas, environmental degradation is attributed to higher geopolitical instability and increased economic activities. Further, Quantile Regression (QR) and Feasible Generalized least square (FGLS) methods are employed to check the robustness empirical findings of the primary techniques. Based on our comprehensive empirical research findings, we can put forth constructive policy recommendations aimed at addressing environmental concerns and achievement of SDGs 7 & 13 in EU region.

1. Introduction

Energy crisis, political upheavals, terrorist attacks, and state and regional instability have aggravated Geopolitical Risks (GPR) at global scale. Terrorism, warfare and stressed international associations are the root cause of GPR (Khan et al., 2023a). It has significance for economies that are vulnerable to the impacts of wars or war-like tensions, terrorism, ethnic strife, and political violence. Further, significant geopolitical catastrophes such as the September 11 attacks, the bombings in London and Madrid, the attacks in Bombay, the trade war between

China and the United States, the nuclear concerns in Korea, and the trade tensions with Iran all provide a substantial risk to the economic stability of an economy (Khan et al., 2023b). Therefore, the Energy Transition (ET) is one the important determinants of environmental quality. The ET involves the shifting from use of conventional energy sources to renewable energy sources. This depends on the structural reforms of the energy sector and the adoption of zero-emission sources. Therefore, the energy transition significantly influences the provision and consumption of energy systems (Nicoli et al., 2025). The ongoing process of transitioning the global energy structure has made significant progress. For a decade, investments in various types of renewable energy have surpassed investments in fossil fuels. Policies will play a crucial role in designing a balanced energy transition by incentivizing investments in clean energy, fostering innovation, boosting energy efficiency, and ensuring equitable distribution of the shift's advantages across all societal sectors. Energy and environmental policies have become increasingly prominent in both domestic and international arenas.

The geopolitical equilibrium of energy has undergone substantial changes, particularly in the manufacturing of renewable energy components, essential minerals, and clean technologies (Saadaoui et al., 2025). The realms of energy innovation have been continuously developed, and a multitude of businesses are diligently striving to revolutionize this expansive business (Panarello & Gatto, 2023). Considering these recent advancements, it has become increasingly crucial for nations to intensify their efforts in the adoption of innovative technologies. The utilization of technology and the advancement of technical innovation have played a significant role in facilitating the reduction of emissions from energy systems on a global scale (Chen et al., 2023). However, to achieve the ambitious objective of attaining global net zero targets, this process must be accelerated.

Further, the implementation of an environmental policy framework that effectively protects the environment while simultaneously fostering economic growth has emerged as a crucial policy approach for mitigating the detrimental effects of environmental deterioration. Regulatory measures have the potential to exert a positive influence on environmental quality by fostering innovation. Stringent regulations, in particular, can stimulate larger levels of innovation as compliance necessitates increased efforts toward a sustainable environment (Maghyereh et al., 2025). Therefore, it is imperative to accurately evaluate the level of stringency exhibited by environmental policies, as only strict policies may positively impact the overall economy and environmental quality. After the year 2015, the rapid growth of the carbon tax was observed as a result of diverse autonomous initiatives undertaken in cities across the United States and Asian nations (Tiwari et al., 2024). The increasing concern of environmental deterioration has prompted numerous governments to actively pursue, discern, and implement the most suitable policy measures in order to attain reduced pollution emissions, while also ensuring sustained economic growth that fosters enhanced social stability. Therefore, EPS is shown to be amongst the critical vital solutions to achieve the target of carbon neutrality in EU region. Moreover, there has been an apparent trend in recent years to intensify initiatives aimed at mitigating CO_2 emissions and shifting towards more environmentally sustainable energy alternatives, owing to the growing urgency of climate change. The Paris Agreement, along with other international climate agreements, has played

a significant role in stimulating worldwide efforts towards carbon reduction. Moreover, to the best of our knowledge, there are limited studies that used this combination of variables and methodology to examine the effect of selected variables on environmental sustainability. This study posits that there may exist inherent relationships between GPR, ET, EPS, INV, and CO_2 emissions, considering the simultaneous challenges associated with these factors. To accomplish this goal, a set of empirical tests is employed to address the subsequent research questions:

1. What are the quantifiable impacts of GPR and INVon carbon dioxide (CO_2) emissions?
2. How does ET and EPS impact CO_2 emissions?
3. How does EPS derive INV and ET nexus for environmental sustainability in the EU region?
4. How does EPS potentially improve the management of GPR while simultaneously attaining carbon neutrality targets?

These research questions highlight the necessity for a revised energy policy paradigm in EU countries. The energy policy rhetoric of the EU countries reveals a significant lack of initiatives aimed at ensuring smooth environmental sustainability in these nations. Although it is crucial to examine the implications of GPR on environmental sustainability, a dearth of empirical investigation is conducted on this matter. Thus, this study extends our understanding and knowledge of the environmental consequences GPR by employing CO_2 emissions as proxy for environmental degradation. Furthermore, the current study also analyzed the effect of interaction of GPR*EPS, INV*EPS, and ET*EPS on CO_2 emissions in the sample countries. The shift towards renewable energy sources is imperative for the mitigation of environmental degradation. The transition to renewable energy sources has significant economic ramifications, impacting various sectors, employment market and general state of economy. Further, it is widely recognized that environmental degradation has adverse implications. Thus, the significance of EPS has surged considerably to maintain a sustainable environment.

The primary objective of the current study examines the moderating role of EPS between geopolitical risk, energy transition, and technical innovation on environmental quality. While previous research has primarily focused on the static components of GPR, this study takes into consideration their dynamic characteristics, specifically on both the long-term effects and at various quantiles. We utilized DOLS, FMOLS, CCR, and MMQR methodologies to provide a thorough analysis. This study holds global relevance attributable to the urgent need to tackle environmental challenges and global extent of global warming. It offers valuable knowledge that could be beneficial for economies at various phases of the development and with diverse resource capabilities. This study has the potential to provide significant energy strategies and promote global collaborations. Why European countries? This research selected EU countries as a sample based on several rationales; First, EU countries ranked 3rd in terms of their significant contributor to GHG emissions in 2021. Germany recorded the highest emission, comprising of 23% of total emissions. Italy and Poland accounted for 11%. The main drivers are transportation (28%), heavy industries (25%), electricity production (22%), construction (13%) and agriculture (12%). Consumption of fossil fuels contributes 80% of overall emissions

in EU region. Second, The EU's policies are designed to tackle challenges that necessitate substantial investments in renewable energy sources, innovative technologies and structures, which could be impacted by GPR. Third, many European Union countries rely on fossil resources obtained from politically unstable territories, such as Russia and the Middle East. This renders businesses vulnerable to interruptions in supply, which hinders their initiatives to transition to more renewable energy sources. Consequently, the EU has placed significant emphasis on enhancing energy security through initiatives such as the Energy Union and the Renewable Energy for All Europeans Program. Third the consequences of environmental degradation have resulted in a rise in migration and relocation, potentially leading to geopolitical turmoil and posing further challenges for EU members in implementing EPs. However, EPs can also contribute to the reduction of GPR and CO_2 emissions. Policies that advocate for energy autonomy and the use of renewable energy sources can decrease a nation's dependency on imported fossil fuels while minimizing the potential for energy supply interruptions. Moreover, the implementation of policies that advocate for the sustainable utilization of resources and the preservation of the environment can effectively reduce the possibility of resource confrontations and environmental deterioration, thereby playing a role in mitigating geopolitical tensions. Considering these disparities, for the present research we have selected 13 EU countries as sample to check the impact of different determinants of CO_2 emissions.

Moreover, in an effort to meet emissions reduction targets EU countries have designed and implemented effective policies for addressing climate change. Promise has been highlighted by recent initiatives, specifically, green deal industrial plan (2020), Fit for 55 plan (2020) and SDGs agenda in EU region. The primary goal is to attain a 55% decrease in CO_2 emissions to achieve SDGs 7 & 13 by the year 2030. This study attempts to analyze the data of EU countries from 1990 to 2020, based on the current policy orientation. The contribution of current study is two folded; Firstly, it suggests a fresh policy insight that prioritize SDGs (7 & 13) to support policymakers in achieving environmental viability and SDGs objectives. Secondly, the empirical results of the study are used to offer policy framework for the EU countries to achieve SDGs (7 & 13). The regulatory framework is globally developed, encouraging other economies to follow it as a benchmark, regardless of their current development stage. The findings of the current study highlight the necessity of environmental policies that encourage green innovations and shift towards renewable energy sources to combat the issue of environmental degradation. Policymakers need to design policies to mitigate CO_2 emissions when there is higher GPR to maintain the long run environmental sustainability. Therefore, it is important to emphasize the significance of reforms in ecological polices that support transition to renewable energy sources and adoption of green innovative technologies.

The remaining structure of the paper is as follows: Section 2 is a literature review. Section 3 comprises of methodological approaches discussion. Section 4 talks about the empirical results. Section 5 demonstrate the conclusions and policy recommendations based on the study findings as well as limitations of the study.

2. Literature review

2.1. Theoretical linking directions

The Porter and Linde Hypothesis (1995), argues that strict environmental regulations can promote innovation, enhance resource consumption efficiently, and encourage sustainable development, thereby amplifying competitiveness. Strict policies can foster green innovation by driving businesses towards employing environmentally sustainable technologies and green practices that alleviate negative environmental impacts. Appropriately, designed rules, particularly sustainable environmental standards might promote optimized conditions, and promoting businesses to participate in sustainable practices. Furthermore, environmental regulations may promote resource effectiveness and sustainability thus eliminating contamination. The Porter Hypothesis contends that environmental regulations might promote sustainable economic development while boosting ecological sustainability, eliminating contaminations, reducing global warming, and protecting natural resources.

2.2. Geopolitical risk and environmental sustainability

Recently GPR has increased globally. Political instability, armed conflicts and terrorism attacks has risen all over the world. GPR affects societies, politics, economies, and the environment. Existing literature indicates that GPR affects economic activities and environmental sustainability distinctively. Several studies demonstrated the GPR hinders economic growth by reducing energy usage (Pengfei et al., 2023; Husnain et al., 2022; Rumokoy et al., 2023), thus lower the environmental degradation (Jiatong et al., 2023). However, GPR also impede innovation activities, restrict the use of innovative technologies, and thus degrades the environment (Chen et al., 2022; Gollakota & Shu, 2023; Hassan et al., 2024; Chen et al., 2024). Thus, scholars and researchers must examine the consequences of GPR on the environment to recommend policies in order to achieve environmental sustainability. Recently various studies examined the association between GPR index and energy consumption and environmental degradation (Ebadi et al., 2020; Zhang et al., 2021; Umar et al., 2022; Bildirici et al., 2022; Luo & Sun, 2024). The study of Rasoulinezhad et al. (2020) demonstrated that GPR increases CO_2 emissions in Russia, while energy transition and financial development reduces the environmental degradation from 1993 to 2018.

2.3. Energy transition and environmental sustainability

Energy Transition (ET) plays a crucial role in maintaining environmental sustainability and fostering economic growth. In the midst of rising temperatures and global warming, ET offers and approach to a sustainable future. Switching from fossil fuels to renewable energy transition, such as Wind, Solar and hydropower, allows governments to significantly reduce CO_2 emissions mitigate, reduce effects of climate change, and improve environmental quality (Streimikiene et al., 2021). The study of Bakhsh et al. (2024) examined the effect of changes in economic complexity, GPR, governance and ET on environmental degradation in OECD countries on the dataset spanning from 1990 to 2021 by employing MMQR approach. Their findings demonstrate that ET contributes to improving environmental quality. Similarly, Cevik

and Ninomiya (2023), examined the impact of ET and electricity prices in 24 EU economies on the dataset spanning from 2014 to 2021 by employing panel quantile regression techniques. They demonstrated that ET is positively associated with environmental sustainability. The worldwide energy sector must develop operative policies to effectively adopt ET. The policies seek to utilize different energy sources that contribute to improving environmental quality and achieve SDGs (Drosos et al., 2020; Brożyna et al., 2023; Adelekan et al., 2024; Bashir et al., 2024).

2.4. Environment policy stringency and environmental sustainability

Environment Policy Stringency (EPS) plays a crucial in achieving economic growth and environmental sustainability in the long run. Governments can establish an infrastructure that encourages sustainable practices and encourages effective use of natural resources by implementing strict environmental regulations (Kyriakopoulos et al., 2023). These measures intend to raise costs associated with contamination and environmental services (Wang et al., 2022). Countries are putting efforts to implement strict environmental regulations globally. The implementation of stricter environmental rules in OECD countries has had a minimal impact on overall productivity development (Ahmed, 2020). However, it has been observed that the increase in EPS has resulted in varying outcomes across different sectors of the economy (Kruse et al., 2022; Dam et al., 2023). Specifically, the industries and firms that are more technologically advanced have had a modest and ephemeral boost in productivity growth. On the other hand, the least productive firms experienced a decline in their productivity levels (Bako et al., 2022; Vaghela et al., 2023). The potential channels for this phenomenon include corporate dynamics, specifically the processes of entry, exit, and expansion, as well as outsourcing and innovation (Liang, 2023; Li et al., 2023a). Similarly, Li et al. (2023b) reveals a notable positive correlation between the level of regulatory strictness in a country and its degree of specialization in the exportation of goods classified as "environmental" items. Therefore, the strictness of environmental rules can impact various aspects of economic activity, including competitiveness and innovation. However, the current body of empirical research on the impacts of rigorous policies is limited and primarily concentrated on particular policies within specific situations.

2.5. Technological innovation and environmental sustainability

Numerous studies have identified the use of technology as a prominent determinant in the mitigation of worldwide CO_2 emissions (Liu et al., 2023). The incorporation of technical innovation in the resolution of societal issues, i.e., water and air pollution has emerged as a relatively new phenomenon (Streimikiene & Kyriakopoulos, 2024; Sharif et al., 2023). The proliferation of novel technology constitutes a crucial component within a holistic approach to addressing the issue of global climate change (Jin & Gambatese, 2020). According to Sharif et al. (2022), to effectively reduce carbon emissions within the global energy system, it is imperative to expedite the implementation of technological advancements that serve two primary goals: (i) maximizing the electrification of energy consumption to the greatest extent feasible, and (ii) eliminating carbon emissions from electricity generation, with a

special emphasis on utilizing renewable energy sources. However, the implementation of technology advancements necessary for such a significant transformation cannot be achieved instantaneously. To attain a significant decrease in CO_2 emissions, nations must undertake the retrofitting or replacement of numerous electric power plants, millions of automobiles, and a multitude of consumer appliances, building systems (heating, cooling, and lighting), as well as industrial processes and equipment. Achieving change on such a scale will need a significant amount of time, spanning several decades (Cheng et al., 2021). Similarly, Lin et al. (2024) examined the impact of digital finance, renewable energy consumption, and technological innovation in 31 Chinese provinces on the dataset spanning from 2011 to 2020. They demonstrated that digital finance and technological innovation has positive impact on sustainability. Their findings encourage the adoption of innovative technologies in order to reduce ecological degradation. Similarly, Aytun et al. (2024) investigated the impact of human capital, financial development, and technological innovation in 19 middle-income countries on the dataset from 1980 to 2016. They employed CS-ARDL approach and concluded that increased level of innovative technologies improves environmental sustainability in sample countries.

2.6. Research gap

Existing literature focused on investigating the effect of GPR, ET, EPS and INV on environmental degradation in China (Dogah et al., 2024), BRICS (Cui et al., 2024; Udeagha & Ngepah, 2023), and OECD countries (Bakhsh et al., 2024). Limited attention has been given to examine the impact of these determinants on CO_2 emissions in the EU region. The aforementioned discussions in the literature provide a valuable discussion on the diverse factors that influence environmental quality. However, this study addresses the lack of knowledge by including all the explanatory variables in a single model to evaluate their impact on CO_2 emissions. There is a lack of extensive research in the context of EU countries. Methodologically, prior research on energy transition, environmental policy stringency, technological innovation, and CO_2 emissions has overlooked the potential presence of slope heterogeneity and cross-sectional dependence in panel data, which can result in biased and deceptive estimates. To tackle this problem, it is imperative to employ suitable estimation techniques to examine the factors that influence CO_2 emissions, to enhance decision-making. Thus, this paper employs innovative DOLS, FMOLS, CCR, and MMQR estimation approaches to tackle panel data issues and yield more reliable research findings. In summary, the literature review revealed varied and inconclusive findings regarding the effects of GPR, ET, EPS, INV, and CO_2 emissions. Moreover, further research is required to examine the long-term and causal relationship among energy transition, environmental policy stringency, technological innovation, and their potential to reduce CO_2 emissions. The results will enhance climate-related strategies in EU nations while encouraging the attainment of carbon neutrality and environmental sustainability.

3. Data and material

3.1. Data

This study utilizes data from 13 European Union (EU) nations spanning from 1990 to 2022. This research aims to investigate the relationship between Geopolitical Risk (GPR), Energy Transition (ET), Environmental Policy Stringency (EPS), Technological Innovation (INV), and carbon dioxide (CO_2) emissions. Further, the study used the interaction terms of INV *EPS, GPR*EPS, and ET*EPS, to check their combined impact on CO_2 emission. The selection of EU countries (See Table A1 in the Appendix) for this study is based on their increasing contribution to the diversification of the global economy. These countries are considered to have strong economies and are actively promoting, energy transition and technological advancements in the field of climate change. The data of certain variables is obtained from the databases of WDI and OECD statistics. The detailed description of variables is presented in Table 1.

Table 1. Variables description

Variables	Description	Proxies	Sources
CO_2 emission	Environmental degradation	Metric tons per capita	World Development Indicator (WDI)
GPR	Geopolitical risk	GPR Index	Matteo.iacoviello
EPS	Environmental policy Stringency	EPS	OECD Statistics
ET	Energy transition	% age of total renewable energy consumption	WDI
INV	Technological innovation	Total patents	OECD Statistics
EG	Economic growth	GDP (Constant 2010 USD)	WDI

Note: Table 1 outlines study parameters and their detailed description. These tables also explain the adopted proxies and data sources.

The proxy used to measure environmental quality is CO_2 emission, which is selected as the dependent variable and is calculated as Metric Tons per Capita. Whereas, independent variables i.e., Geopolitical Risk (GPR) is measured as GPR index, EPS is measured as EPS index, ET is measured as %age of total renewable energy consumption, technological innovation is measured with patent applications, economic growth (EG) is measured using constant 2010 USD and GDP growth (annual %age). The data for selected variables is collected from OECD statistics, World Development Indicators (WDI), and International Court Risk Guide (ICRG) databases.

3.2. Theoretical underpinning

GPR index, which has been proposed by Caldara and Iacoviello (2018) has been used as proxy of GPR. Despite the considerable importance of previous research and its findings, the indicators used to represent geopolitical events possess certain limitations. These limitations include the inability to capture real-time data, the presence of gaps in data collection, and the failure to encompass the full spectrum of actual geopolitical events. This measurement

does not capture the proper depiction of GPR (Bouoiyour et al., 2019). Whereas, GPR index measures the risk level that occurred due to armed conflicts, terrorists attack, political instability, and geopolitical uncertainties. GPR index is more appropriate proxy because it considers both current and anticipated future risks (Khan et al., 2023b).

Energy Transition (*ET*): ET is the shifting from no renewable energy sources to renewable energy sources. ET plays a crucial role in maintaining environmental sustainability. It is important to monitor the renewable sources consumption pattern in the EU region to check its contribution to a sustainable environment (Tiwari et al., 2024). This parameter captures the evolution of renewable energy sources consumption and environmental degradation.

Environmental Policy Stringency (*EPS*): EPS is the degree of implantation of environmental policies and regulations strictly by every country. EPS index is an appropriate representation regulation framework and level of commitment to overcome environmental concerns (Ahmad et al., 2024). This parameter captures the effect of environmental policy stringency in EU region.

Technological Innovation (*INV*): INV represents innovative and updated environmentally friendly technologies that contribute to lower environmental degradation and maintain environmental sustainability (Bergougui, 2024). Measuring patents to depict development in innovative technologies that help to reduce environmental degradation in EU countries is crucial.

Economic Growth (*EG*): The higher EG in any country due to an increase in human activities is subject to various factors. The increase in human activities for EG affects environmental sustainability due higher combustion of fossil fuels, and inappropriate use of available resources thus causing environmental degradation and climate change (Ritchie, 2024). Capturing the impact of EG on the environment of EU countries is important due to its consequences on human well-being and the environment.

3.3. Model specification

In current study, an econometric analysis of panel data has been employed for numerous reasons, Firstly, by integrating the time series and cross-sectional measurements, panel data provide more observations, which improves the statistical accuracy and potential to conclude (Hassan et al., 2020). Secondly, panel data analysis reveals effect that are not detectable in cross sectional and time series analysis (Plümper et al., 2005). Furthermore, panel data provide more meaningful statistics, greater variations, less collinearity across parameters, a greater degree of freedom, and more effectiveness (Baltagi et al., 2005). Therefore, the following study model has been employed to check the nexus of the selected series of variables.

$$CO_{2it} = f\left(GPR_{it}, ET_{it}, EPS_{it}, INV_{it}, EG_{it}\right). \tag{1}$$

The following econometric model:

$$CO_{2it} = \vartheta_0 + \vartheta_1 GPR_{it} + \vartheta_2 ET_{it} + \vartheta_3 EPS_{it} + \vartheta_4 INV_{it} + \vartheta_5 EG_{it} + \mu_{it}; \tag{2}$$

$$CO_{2it} = \vartheta_0 + \vartheta_1 GPR_{it} + \vartheta_2 ET_{it} + \vartheta_3 INV_{it} + \vartheta_4 INV*EPS_{it} + \vartheta_5 EG_{it} + \mu_{it}; \tag{3}$$

$$CO_{2it} = \vartheta_0 + \vartheta_1 GPR_{it} + \vartheta_2 ET_{it} + \vartheta_3 INV_{it} + \vartheta_4 GPR*EPS_{it} + \vartheta_5 EG_{it} + \mu_{it}; \tag{4}$$

$$CO_{2it} = \vartheta_0 + \vartheta_1 GPR_{it} + \vartheta_2 ET_{it} + \vartheta_3 INV_{it} + \vartheta_4 ET*EPS_{it} + \vartheta_5 EG_{it} + \mu_{it}, \tag{5}$$

where i, t indicates countries and time period while μ_{it} represents error term in the above Equation. Carbon dioxide (CO_2) emission is used as dependent variable whereas Geopolitical Risk (GPR), Energy Transition (ET), Environmental Policy Stringency (EPS) Technological Innovation (INV) and Economic Growth (EG) are used as explanatory variables. Figure 1 illustrates the seven steps of the estimation process carried out for analysis and are explained in subsequent section. The estimation approach entails a set of procedures for evaluating the associations of parameters. A CD test is performed because it may produce error and irregular estimates of coefficients of regression. A slope of homogeneity test is executed to check whether the association between two parameters remained similar across multiple units. Next, a unit root test is performed to determine the degree of stationarity or non-stationarity of the dataset. Then Panel cointegration test is performed to check the long-run association among the selected parameters. Long-run estimation methods i.e., DOLS, FMOLS, CCR, and MMQR are employed to check the long-run association among the variables. Then FGLS and Quantile regression is performed to check the robustness of the results. At last, Panel Granger Causality test is executed to analyze the casual association among study parameters.
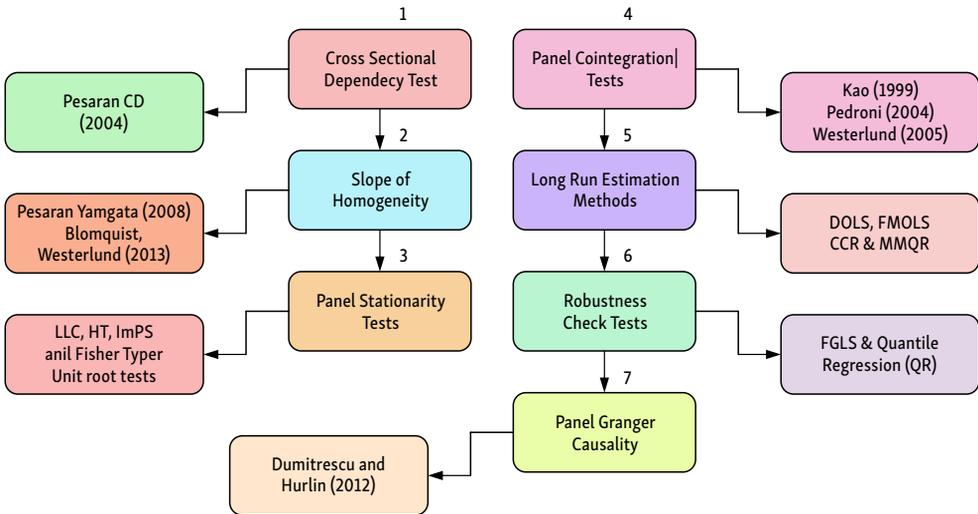

Figure 1. Estimation analysis roadmap

3.4. Panel estimation technique

To capture the long-run impact of explanatory variables on explained variables, the current research has employed distinct econometric approaches, Dynamic Ordinary Least Square (DOLS) developed by Kao (1999), Fully Modified Ordinary Least Square (FMOLS) proposed by Pedroni (2001), Canonical Cointegration regression (CCR) suggested by Park (1992) and latest Method of Moment Quantile Regression (MMQR) model developed by Machado and Silva (2019). These methods are appropriate to handle endogenous parameters and capture the specific effects of individual. The DOLS technique has been employed to investigate short- and long-term fluctuations across the parameters. FMOLS method has been utilized to alleviate endogeneity and serial correlation problems. While, CCR method is used to de-

termine the fundamental trends and correlation among the selected parameters, allowing more deeper understanding their relationship.

Moreover, MMQR illustrates its capacity to provide appropriate estimations under different situations, specifically when fundamental models exhibit non-linearity. In contrast to different nonlinear techniques for instance NARDL approach, MMQR is used at higher frequency. Given the previously indicated underlying objectives, the MMQR technique is widely regarded as the most suitable methodology for investigating both asymmetric and nonlinear correlations. Furthermore, it effectively tackles the concerns surrounding heterogeneity and endogeneity. The MMQR exhibits an intrinsic tendency by generating estimations that are distinct among structural quantiles. The present study utilized these techniques to produce accurate and robust estimations of the associations across the parameters thus strengthen the current body of literature.

This paper presents following comprehensive description of the conditional quantile estimations for the locational scale variant model.

$$Yit = \vartheta i + wit'\Delta + \left(\gamma i + Xit'v\right)Uit. \tag{6}$$

ϑ, Δ, γ, v indicates the vectors of the variables, while P ($\gamma i * Xit' * \tau > 0$) illustrate the probability factor.

(ϑi, γi) with $i = 1, 2, 3, ..., n$ demonstrate the fixed effects for each i. The matrix X is a k-vector that contains specified components of W, which are distinct transformations with the l-th component, particularly defined as:

$$Xl = Xl\left(W\right), \, l = 1, ..., k.$$

Eq. (3) indicates that Wit is dispersed uniformly and consistently among individuals at certain time. Likewise, *uit* factor exhibits equal distribution across all *i* and *t*, and it adheres the standardized criteria stated in Machado and Silva's (2019) study.

$$QY\left(\frac{\tau}{Wit}\right) = \left(\vartheta i + \gamma iq\left(\tau\right)\right) + Wit'\Delta + Xit'vq\left(\tau\right).$$

In the above Equation, the vector Xit denotes the explanatory variables, including GPR, ET, EPS, INV, EG, INV*EPS, GPR*EPS, and ET*EPS. On the other hand, QY (τ/*Wit*) represents the explained variable, i.e., CO_2 emission.

3.5. Multicollinearity test

The effective use of the Variance Inflation Factor (VIF) test is a prevalent approach to detect the presence of multicollinearity. The estimation quantifies the degree to which the variability of a predicted regression variable is augmented as a result of its linear dependence on other explanatory factors (Hassan et al., 2021). According to Kennedy (1993), the potential indication of unsuitable collinearity arises when the value of the Variance Inflation Factor (VIF) index is above 10. Therefore, this criterion is utilized to detect the existence of multicollinearity in the regression analysis. The issue of multicollinearity may arise when there are significant correlations among numerous explanatory variables inside a model. The observed trend possesses the capacity to induce a significant increase in the standard errors of parameters and the occurrence of estimations of coefficients that may be deemed „incorrect," so undermining the validity of statistical inferences.

3.6. Cross Sectional Dependence (CD) test

The assessment of the CD test has paramount significance in selecting appropriate econometric methods for analyzing data, especially in the framework of panel data analysis. According to Pesaran et al. (2004), unit root analysis and cointegration testing are prior tasks. Existence in one country can spread quickly to the neighbouring. The CD test has been used to evaluate the prevalence of CD in certain selected nations. According to the null hypothesis, there is no CD among the chosen nations. For research with a small sample size N (number of nations) and a long time period T, or $N < T$, the Breusch and Pagan (1980) Lagrange Multiplier (LM) is appropriate. The findings are summarized in Table 4.

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{I=i}^{N-1} \sum_{J=i+1}^{N},$$

where CD = 1, 2, 3, 4, 5, …, N.

3.7. Unit root test

Unit root tests are typically performed on the data to determine stationarity before using econometric techniques to analyze the relationships between variables. The Im-Pesaran Shin (IPS) (2003) test, the Levin Lin Chu (LLC) (2002) test, the Harris-Tzavalis (HT) (1999) test, and the Fisher Type (FT) (Choi, 2001) test are the most common panel unit root tests used in the current study. ADF-type and Perron-type approaches were employed in the study to execute the testing. The multiple panel unit root tests have two distinguishing features. Different autoregressive dynamics are being taken into account. The underlying assumption of the LLC and HT tests is that all panels display a common autoregressive process.

Further evaluations, including the IPS and FT, permit the detection of the panel-specific autoregressive process (Choi, 2001; Baltagi et al., 2013). Additionally, there exist contradictions between the tests' basic assumptions regarding the infinite nature of either the sample size, denoted by N, or the number of time periods, denoted by T, or whether N or T remains constant. Choi (2001) and Baltagi et al. (2013) pointed out that whereas the LLC, FT-ADF, and FT-P tests demand that N be relatively small in proportion to T, the HT and IPS tests allow for the asymptotic behaviour of N approaching infinity. The variable N, which stands for the period's associated number, serves as the panel's identifier. As a consequence, it is considered that the assumption of a constant variable N is more robust.

3.8. Cointegration test

A cointegration study is carried out to assess the long-term connection between the chosen variables. In contrast to model estimates produced from individual time series, panel cointegration addresses show greater accuracy. The dependability of the results is strengthened by the use of model estimates, which provides greater flexibility when examining time-series cross-section data. As a result, the current study employs Kao (1999) and Pedroni (2004) cointegration tests, two different panel cointegration models. We used the cointegration test suggested by Westerlund and Edgerton (2007), which employs the bootstrap approach to lessen the possible influence of cross-sectional dependency across variables, to address these issues.

4. Results and discussion

4.1. Descriptive statistics

To determine the impact of GPR, ET, EPS, INV, EG, INV*EPS, GPR*EPS, and ET*EPS on environmental quality, specifically CO_2 emissions, our panel data approach begins with examining the trends and patterns of the data. Table 2 demonstrates the results of descriptive statistics.

Table 2. Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
CO_2	0.8852389	0.1288385	0.5109455	1.144309
GPR	0.3225699	0.2162002	–0.3802113	0.6892102
ET	1.026821	0.4371146	–0.0268721	1.766413
EPS	–0.0628357	0.4622841	–1.361429	1.06406
INV	2.297629	0.926458	0.4166667	4.22222
GDP	1.34878	0.0612023	1.165307	1.740005
INV *EPS	–0.1142008	1.18623	–4.765001	4.315356
GPR*EPS	–0.0148809	0.189465 8	–0.5214636	0.6438262
ET*EPS	–0.1162451	0.5484868	–1.958904	1.197234

Table 2 presents the descriptive statistics of the selected variables. The results of descriptive statistics indicates that CO_2 average value is 0.8852389 with standard deviation of 0.1288385 while the minimum value is 0.5109455 and maximum value is 1.144309. The study's findings indicate that the average value of GPR is 0.3225699, with a standard deviation of 0.2162002. On the other hand, the minimum value is –0.3802113 and the maximum value is 0.6892102. Results demonstrate that the mean value of ET is 1.026821, while standard deviation is 0.4371146 with minimum value of –0.0268721 and maximum value of 1.766413. The average value of EPS –0.0628357 with standard deviation of 0.4622841, while minimum and maximum value is –1.361429 and 1.06406, respectively. Whereas, INV possess average value of 2.297629 with standard deviation of 0.926458. INV has the minimum and maximum value of 0.4166667 and 4.22222 respectively.

4.2. Multicollinearity test

Table 3 illustrates the outcomes of the VIF test, which is conducted to assess the presence of multicollinearity among the selected research variables. The findings from the VIF test indicates that the selected variables do not show multicollinearity.

All variables in the study exhibit significance levels that surpass 0.2, indicating that they are not statistically significant. Additionally, the VIF values for all variables are below 5, suggesting that the parameters do not exhibit any considerable multicollinearity.

Table 3. VIF test

Variable	VIF	1/VIF
GPR	2.52	0.396466
INV	2.25	0.443914
ET	1.45	0.689837
EPS	1.13	0.887534
GDP	1.02	0.981304
Mean VIF	1.67	

4.3. Average correlation coefficients & Pesaran (2004) CD test

Cross-sectional dependency is one of the most significant diagnostic tests before doing a panel data analysis. The effect of cross-sectional dependency on estimates depends on various factors i.e., degree and form of CD test itself. The findings of CD test are demonstrated in Table 4. The results derived from the cross-sectional dependence (CD) tests indicate that the null hypothesis, which posits the absence of cross-sectional dependence, may be rejected at a significance level of 1%. The cross-sectional dependency test indicates that every country is dependent on another country.

Table 4. Average correlation coefficients & Pesaran (2004) CD test

Variable	CD-test	p-value	corr	abs(corr)
CO_2	31.42	0.000	0.639	0.655
GPR	44.87	0.000	0.912	0.912
ET	40.90	0.000	0.832	0.832
EPS	19.18	0.000	0.390	0.397
INV	46.07	0.000	0.937	0.937
EG	12.62	0.000	0.257	0.328
GPR*EPS	9.16	0.000	0.186	0.378
INV*EPS	10.63	0.000	0.216	0.349
ET*EPS	13.70	0.000	0.279	0.316

Note: Under the null hypothesis of cross-section independence CD~N (0,1).

4.4. Slope of homogeneity test

Various political, social, and economic variables can lead to variations among countries in terms of innovation, geopolitical situations, policy implementation, and decision-making. It is vital to examine if the slope in the data is homogeneous or heterogeneous to avoid biased conclusions in the estimation. Thus, the slope features of the data are determined using the Pesaran and Yamagata (2008) and Blomquist and Westerlund (2013) tests. Table 5 demonstrates the results of the slope of homogeneity.

The findings of the slope test reveal that the null hypothesis is rejected, implying that the slope coefficients are not homogeneous but exhibit significant variation among countries.

Table 5. Slope of homogeneity

	Delta	P-Value
Pesaran and Yamgata (2008)		
Δ	14.001	0.0000
Δ~Adjusted	16.619	0.0000
Blomquist and Westerlund (2013)		
Δ	12.835	0.0000
Δ~Adjusted	15.236	0.0000

4.5. Unit root test

To determine the stationarity of the data, unit root tests are required before employing an econometric technique to check the long run association among selected variables. Table 6 demonstrate the results summary of unity root tests. The results of LLC indicate that selected variables i.e., CO_2 and ET have unit root problem at I (0) but become stable at I (I). While GPR, EPS, INV and EG are stable at both I (0) and I (I). The results of *HT* test indicates that CO_2, GPR, ET and INV are not stable at level I (0) and become stable at I (I). while EPS and EG is stable at both I (0) and I (I).

The IPS and FT tests are widely employed techniques to determine the stationarity of the variables. The current study uses the two cross-section tests developed by Pesaran et al. (2004), the IPS test, and FT test, to check the stability of the parameters. This panel unit root test relies on the asymptotic assumption, contributing to its improved accuracy and resilience. The results of the FT test show that CO_2, GPR, ET, and INV are not stable at the I (0). However, these become stable at I (I) when 1% significance is considered. The results show that all the variables are stable in both I (0) and I (I). This suggests that the long-term associations between the selected variables can be examined by employing the MMQR model.

Table 6. Panel unit root test

Variables	Levin-Lin-Chu (LLC) unit-root test		Harris-Tzavalis (HT) unit-root test		Im-Pesaran-Shin unit-root test		Fisher-type (FT) unit-root test	
	At Level	First Diff	At Level	First Diff	At Level	First Diff	At Level	First Diff
CO_2	7.4500	–2.3119***	1.8846	–33.393***	6.0649	–10.8485***	4.9883	–16.9689***
GPR	–1.503**	–7.2022***	0.6756	–34.5547***	0.3824	–12.2964***	0.2977	–20.1167***
ET	2.5445	–6.2422***	3.5887	–33.3042***	6.8038	–10.9351***	5.9653	–16.9565***
EPS	–5.2814**	–10.3325***	–18.5276**	–44.0316***	–6.9303**	–13.0443***	–8.8443**	–23.0521***
INV	–0.7938**	–8.6933***	2.0245	–34.5194***	2.7003	–11.2435***	3.001	–17.5654***
EG	–2.5745**	–10.4238**	–2.7614**	–30.7095***	–2.4838**	–9.6603***	–2.7515**	–13.9719***
INV *EPS	–2.4461*	–10.5236***	–8.7240***	–43.5983***	–4.1178***	–12.7765***	–4.9914***	–22.0880***
GPR*EPS	–2.3217*	–10.5091***	–7.3584***	–43.5334***	–3.7900**	–12.7805***	–4.4858***	–22.1128***
ET*EPS	–3.7081*	–10.4910***	–16.5098***	–44.0241***	–5.6168***	–12.8099***	–7.1202***	–22.2503***

4.6. Cointegration test

Cointegration test intends to determine the level of vulnerability of variables to the same average value over a certain period. Cointegration test intends to examine the level of vulnerability of variables to the same average value over a certain period of time. The first and second generation cointegration tests i.e., Kao, Pedroni and Westerlund have been employed to examine the cointegration among study variables.

The outcomes of cointegration tests are summarized in Table 7. The test results are significant which indicates that selected variables are cointegrated.

Table 7. Cointegration tests

Kao test	Statistic	p-value
MDFt	−22.9822	0.0000
DFt	−19.1540	0.0000
ADFt	−10.0894	0.0000
UMDFt	−33.6715	0.0000
UDFt	−20.1261	0.0000
Pedroni Test		
MPPt	−1.8628	0.0312
PPt	−12.7489	0.0000
ADFt	−9.8327	0.0000
Westerlund Test		
Variance ratio	3.6994	0.0001

4.7. Long run estimation technique

The significance of the sustainability of the environment has increased substantially due to its crucial role in both EG and human well-being. This has culminated in the formation of collaborations between nations and international agencies, who have implemented effective policies in response to growing concerns for environmental degradation.

Table 8 demonstrates the results of DOLS, FMOLS, and CCR methods. The coefficients of GPR and GDP are positive and statistically significant. This indicates that with a rise of 1% in GPR, environmental degradation increases by 0.33539, 0.35401, and 0.35609 in DOLS, FMOLS, and CCR respectively. Similarly, the results indicate a 1% increase in EG upsurges CO_2 emissions by 0.14330, 0.14118, and 0.13538 in DOLS, FMOLS, and CCR approaches, respectively, due to higher economic activities. This posits that at time of geopolitical instability, armed conflicts, and terror attacks, economies become vulnerable and environmental degradations increases due to use of non-renewable sources. These findings are in line with the study of Hunjra et al. (2024). They analyzed the effect of INV, GPR, and institutional governance on environmental quality by using AMG and CS ARDL techniques. They concluded that higher GPR exacerbate environmental quality. Whereas, effective governance and green investments contribute to increase environmental sustainability.

Table 8. Long run estimation

Variables	DOLS		FMOLS		CCR		FGLS	
	Coeff.	Std. Err	Coeff.	Std. Err	Coeff.	Std. Err	Coeff.	Std. Err
GPR	0.33539***	0.14305	0.35401***	0.1005	0.35609***	0.10507	0.318725***	0.033602
ET	−0.18804***	0.05063	−0.1847***	0.03778	−0.1857***	0.03788	−0.18587***	0.012599
EPS	−0.05297***	0.0445	−0.0416***	0.03144	−0.0411***	0.03253	−0.05161***	0.010503
INV	−0.08606***	0.03098	−0.0953***	0.02215	−0.0959***	0.02267	−0.08120***	0.007410
GDP	0.14330**	0.34466	0.14118**	0.22574	0.13538**	0.23707	0.14026**	0.075448
INV *EPS	−0.009297**	0.017194	−0.005673**	0.012513	−0.0053853**	0.0129335	−0.0109801**	0.0041023
GPR*EPS	−0.1006742**	0.106682	−0.085086**	0.075926	−0.083467**	0.078570	−0.1104086***	0.0256910
ET*EPS	−0.0333856**	0.0398086	−0.020973**	0.028456	−0.0205542**	0.0292092	−0.034292***	0.0092511
_cons	0.97110***	0.47204	0.98792***	0.30876	0.99747***	0.32452	0.96743***	0.103203

Further, results demonstrate that the coefficients of ET, EPS and INV are statistically significant and negative. This suggests that a 1% increase in the shift from traditional energy sources to renewable energy sources lowers CO_2 emissions in EU countries by −0.18804 in DOLS, −0.1847 in FMOLS, and −0.1857 in CCR. Similarly, a 1% increase in the implementation of environmental policies strictly contributes to lower CO_2 emissions by −0.05297, −0.0416, and −0.0411 in DOLS, FMOLS, and CCR respectively. Furthermore, INV is also negatively and statistically significant with CO_2 emissions. This implies that a 1% increase in the adoption of innovative technologies reduces CO_2 emissions by −0.08606 in DOLS, −0.0953 in FMOLS, and −0.0959 in CCR. These results demonstrate that transition from traditional energy sources to renewable energy sources, implementation of strict environmental regulations i.e., climate, taxes, and energy taxes, and adoption of innovative green technologies has the potential to curb the issue environmental degradation in EU region. These outcomes are in line with the study of Ahmad et al. (2024). Their study checks the effect of ET, green technologies, and EPS in European economies. They employed CCE-MG on the dataset from 1994 to 2019 and concluded that these parameters effectively lower CO_2 emissions and enhance environmental quality.

The current study findings suggest that the consumption of RE sources, adoption of INV, and implementation of strict environmental rules are the effective approaches to achieve SGDs (7 & 13) by 2030 in EU region. The notion is supported by the findings, which demonstrate a negative and statistically significant coefficient of EPS, emphasizing the negative association of EPS and environmental degradation (Tiwari et al., 2024). The negative relationship between the strictness of policies and environmental degradation highlights the significant impact of stringent policies in mitigating CO_2 emissions and fostering sustainable growth in EU region. Further, the aim of technological innovation is crucial to comprehend the detrimental external effects on sustainability resulting from elevated economic activities. However, the majority of the technologies owned by developed economies have achieved a state of technical maturity and have become obsolete, thereby failing to harness their associated advantages (Chatti & Khan, 2024). During the COP27 meeting, there was a strong emphasis on the importance of technical innovations. The members reached an agreement to prioritize addressing technological challenges to attain zero emissions target by 2050.

Furthermore, the results of the interaction term of INV*EPS demonstrate a negative association with CO_2 emissions. This shows that a 1% increase in INV*EPS, decreases CO_2 emissions by –0.009297, –0.0056732, and –0.0053853 in DOLS, FMOLS, and CCR respectively. This implies that this interaction term INV*EPS plays a vibrant role in encouraging environmental sustainability. These study findings are in line with the outcomes of Xie et al. (2023). They analyzed the effect of EPS on driving green INV for environmental sustainability in OECD countries. They employed MMQR approach and concluded that EPS and INV play crucial roles in mitigating environmental degradation. EPS promotes green technologies through sustainable practices to decrease the CO_2 emissions level.

These findings posit that EPS catalyze INV, driving businesses to adopt INV and green practices to alleviate environmental degradation. This synergic association gives complementing implications, boosting environmental sustainability and enhancing resource optimization. Sustainable energy solutions, for instance, hydropower, solar, wind, and sustainable transportation i.e., electric vehicles, emerge directly from EPS-driven innovation. The positive association of INV*EPS further encourages sustainable investments providing economic benefits. Relevant industries such as green infrastructure gain benefits from this synergy. However, effective policies and global collaborations are vital for harnessing the potential INV*EPS relationship.

Similarly, the interaction of GPR*EPS shows a negative effect on CO_2 emissions. This shows that a 1% increase in combined effect of GPR*EPS lowers CO_2 emissions by –0.1006742 in DOLS, –0.085086 in FMOLS, and –0.083467 in CCR. This implies that EPS has an impact on the association between GPR and CO_2 emissions. These outcomes align with the study of Luo and Sun (2024). In broader term, EPS contributes as a vital moderator. When GPR is highly diligent EPS minimizes adverse environmental effects by deploying emissions monitors, endorsing green practices, and maintaining regulatory adherence. However, moderate EPS could exacerbate the negative consequences of GPR, enabling environmental degradation to boost further. The countries with Stringent EPS, the environmental effects of war or political turmoil are alleviated due to developed protections. In contrast, the regions with adequate EPS might encounter amplified environmental degradation as a consequence of GPR. Therefore, the moderating role of EPS underscores the crucial role of effective environmental regulation in mitigating the detrimental effects of GPR.

Further, the interaction term of ET*EPS demonstrates a negative influence on environmental degradation. The signifies that 1% increase in ET*EPS, decreases CO_2 emissions by –0.0333856, –0.020973, and –0.0205542 in DOLS, FMOLS, and CCR. These findings posit that environmental sustainability is substantially influenced by the synergic association in the EU region. These results align with the findings of Zhu et al. (2024). Thus, ET*EPS emerges as a significant catalyst for environmental sustainability as EU countries try to minimize CO_2 emissions and alleviate the effects of global warming. Further, EPS that imposes rules, perks, and regulations intensify ET practices, for instance, efficient use of RE sources and energy optimization practices. This integrated effect of ET*EPS encourages carbon carbon-neutral economy, eliminates contaminations, and preserves biodiversity. Adequate adoption of ET*EPS in the EU region can provide additional benefits i.e., economic development, improved quality of life, and better environmental management. Hence, comprehending the association of ET*EPS is vital for policymakers to restructure and enact evidence-based strategies to encourage EU countries towards a sustainable environment and green future.

4.8. MMQR analysis

In general, the results obtained from conducting unit root tests and panel cointegration analyses provide strong empirical support for the utilization of the MMQR model as a primary estimator. The findings of the MMQR estimator are presented in Table 9.

The results demonstrate that GPR is positively associated with CO_2 emissions across various quantiles. This indicates that a 1% surge in GPR degrades the environment by 0.34738, 0.32799, 0.30878, and 0.29269 from quantile 20th to 80th. First, this suggests that during the period of higher GPR, governments increase investment spending which increases production and consumption patterns thus leading to increased CO_2 emissions (Bilgin et al., 2020). Second, when countries are confronted with higher political and economic turmoil due to higher GPR, businesses may decide to switch to conventional and inexpensive energy sources consequently increasing CO_2 emissions levels (Chu et al., 2023). Third, it is recommended that during political and economic turmoil and higher GPR, governments focus on tackling these issues and do not concentrate on environmental aspects resulting in higher environmental degradation. This posits that GPR contributes to increased CO_2 emissions and thus degrades the environment.

Table 9. MMQR estimation results

Variables	Location Parameters	Scale Parameters	Quantiles			
			0.2	0.4	0.6	0.8
GPR	0.31873***	–0.02517	0.34738***	0.32799***	0.30878***	0.29269***
	(–0.03667)	(–0.02445)	(–0.05477)	(–0.04141)	(–0.03365)	(–0.03438)
ET	–0.18587***	0.05072***	–0.24362***	–0.20453***	–0.16583***	–0.13340***
	(–0.01269)	(–0.00846)	(–0.01816)	(–0.0146)	(–0.01195)	(–0.01242)
EPS	–0.05161***	0.01450**	–0.06812***	–0.05694***	–0.04588***	–0.03660***
	(–0.01248)	(–0.00833)	(–0.0186)	(–0.01411)	(–0.01148)	(–0.01173)
INV	–0.08121***	0.00629	–0.08837***	–0.08352***	–0.07872***	–0.0747***
	(–0.00827)	(–0.00551)	(–0.01234)	(–0.00933)	(–0.00759)	(–0.00775)
GDP	0.14026***	–0.10671*	0.26175**	0.17953**	0.09811**	0.02989**
	(–0.08088)	(–0.05393)	(–0.12038)	(–0.09147)	(–0.07437)	(–0.0761)
GPR*EPS	–0.110409***	0.0511406*	–0.1688506***	–0.1318203***	–0.0901615***	–0.0560706***
	(0.032178)	(0.020171)	(0.0444256)	(0.0358126)	(0.0309903)	(0.032987)
INV *EPS	–0.0109801***	0.009327*	–0.0218334***	–0.0138253***	–0.0072489***	–0.0008539***
	(0.0051446)	(0.003179)	(0.0069428)	(0.0055051)	(0.0050276)	(0.0055121)
ET*EPS	–0.034292*	0.013017	–0.0492178***	–0.0392663***	–0.028961***	–0.0203365***
	(0.0113542)	(0.007148)	(0.0159857)	(0.0125494)	(0.0107879)	(0.0114419)
_cons	0.96743**	0.16138*	0.78370***	0.90805***	1.03121***	1.13435***
	(–0.11135)	(–0.07424)	(–0.16582)	(–0.126)	(–0.10243)	(–0.10481)

These results depict that ET and CO_2 emissions are significantly and negatively associated with each other across all quantiles. This indicates that a 1% rise in switching to renewable energy sources from traditional sources, decreases CO_2 emissions by 0.24362 to 0.13340 from quantile 20th to 80th. This indicates that ET has the potential to increase environmental sustainability in EU countries. Thus, governments of EU countries must encourage the use of renewable energy sources to achieve sustainable environment targets by mitigating CO_2 emissions. These findings are consistent with the study of Wang et al., (2024). They analyzed the impact of ET, environmental governance, globalization, and EG in the top 10 CO_2-emitting countries on the dataset from 1995 to 2019. They employed the MMQR approach and concluded that the selected variables contribute to lower CO_2 emissions and enhance environmental quality. While an increase in economic activities leads to more EG thus increasing environmental degradation.

Similarly, the coefficients of the EPS are significantly negative demonstrating a reduction in CO_2 emissions by −0.06812, −0.05694, −0.04588, and −0.03660 from quantile 20th to 80th. These findings suggest that the implementation of strict environmental policies for instance environmental taxes and levies contributes to lower environmental degradation in EU economies. EPS is broadly regarded as an effective policy decision for controlling emissions and maintaining environmental sustainability. These findings are consistent with the findings of Luo and Sun (2024). They examined the impact of EPS on ecological footprints in the 11 largest economies on the dataset spanning from 1992 to 2020. They concluded that EPS contributes to decreased CO_2 emissions and thus increases environmental quality. Therefore, it can be contended that it is essential to design a comprehensive policy framework that can be strictly implemented to achieve the SDGs (7 & 13) by 2030.

The interaction of GPR*EPS indicates a negative impact on CO_2 emissions across all quantiles. This indicates that a 1% increase in GPR*EPS decreases CO_2 emissions by −0.1688506, −0.1318203, −0.0901615, and −0.0560706 from the 20th to 80th quantile. The GPR*EPS significantly affects environmental quality in the EU region, while EPS positively moderates this association. These outcomes align with the work of Saliba (2024). Policy intervention for GPR, such as diversification of energy resources, environmental diplomatic efforts, have a critical role in effecting environmental sustainability with EPS. Thus, recognizing the GPR*EPS interaction is crucial for policymakers. The optimal incorporation of these policy measures with EPS enables countries to effectively control GPR, stimulate environmental sustainability, and accomplish sustainability targets, consequently boosting their resiliency to global ecological and geopolitical challenges.

In conjunction with an all-encompassing policy framework pertaining to renewable energy, energy efficiency, and energy accessibility, regulatory frameworks must be coordinated with a resilient, ambitious, and credible plan to achieve net zero emissions (Xie et al., 2023). This strategy should be reinforced by the implementation of effective carbon pricing mechanisms. A conducive investment environment plays a significant role in facilitating the mobilization of greater amounts of capital for the sustainable environment. Furthermore, it is imperative for EU economies to fulfill their obligation of generating a yearly sum of $100 billion in climate funding to support the development efforts of nations in need.

Environmental quality is always inclusive of technological innovation. The study results demonstrate that when a country exhibits a higher level of adoption of INV plays a substantial

role in lowering CO_2 emissions and improving the quality of the environment. It can be argued that the negative implications of technical innovation are often attributed to the implementation of novel technologies, patents, or preservation of the environment measures. The effects exhibited a consistent heterogenous from quantile 20th to 80th. The diverse effects can be explained by one primary factor which is the investment made in innovations and R&D. By consistently allocating resources to innovative activities, the quality of technology can be enhanced. This enhancement offers advantages not just in the context of modifying current equipment or techniques associated with carbon reduction, but also in expediting the development of novel equipment, techniques, and patents. Therefore, a correlation can be observed between technological innovation and the reduction of CO_2 emissions. These results are in line with the research of Churchill et al. (2019). They conducted an empirical analysis that further supports the notion that innovative technologies can effectively contribute to the mitigation of CO_2 emissions by leveraging scale effects and efficient marketing strategies. Regarding the EU countries, there is a variation in the level of adoption of innovative technologies across various countries.

The advancement of sustainable energy has been consistent over the years with significant fluctuations. In recent years, there have been significant accomplishments achieved as investments in low-carbon energy technology exceeded a significant threshold of $1 trillion for the first time. The bilateral finance flows and early-stage financing showed a steady increase, while the total funding for global climate technology venture capital reached a substantial amount of $82 billion (Herman, 2023; Beaurain et al., 2023). To enhance the availability of clean energy and its corresponding technologies, it is imperative to augment the innovation panorama pertaining to clean energy solutions, including alternative fuels, hydrogen, and carbon capture and sequestration (Zhang & Ding, 2022). Policies have a crucial role in facilitating innovation, promoting growth, and influencing the development of energy systems to effectively incorporate emerging technology. The prompt and widespread adoption of clean and efficient energy technology is necessary to attain net-zero emissions. For environmental sustainability, EU economies are currently incorporating their climate, energy security, and industrial policies into more comprehensive frameworks to achieve SDGs (7 & 13). Prominent policies include the Fit for 55 package, the REPowerEU initiative, and SDGs agenda in the European Union region. Following Figure 2 indicates the impact of explanatory parameters on CO_2 emissions across different quantiles. This validates that ET, EPS, INV contributes to lower CO_2 emissions while GPR and EG increases environmental degradation across different quantiles.

4.9. Robustness check

The present work utilized the Feasible Generalized Least Square (FGLS) and Quantile Regression (QR) methods to conduct a robustness check of DOLS, FMOSL, CCR, and MMQR estimate, hence improving the reliability of our estimation results. The utilization of a Feasible Generalized Least Squares (FGLS) estimator offers a more efficient methodology for analysis, as it consistently estimates the substantial error covariance matrix in the presence of heteroskedasticity, serial correlations, and cross-sectional correlations. The estimation results from the FGLS study are presented in Table 8. Based on the results shown in Table 8, it can be observed that there exists a persistent negative correlation between ET, EPS INV, and CO_2 emissions. Whereas, GPR and EG are positively correlated with the environmental quality in selected sample countries.
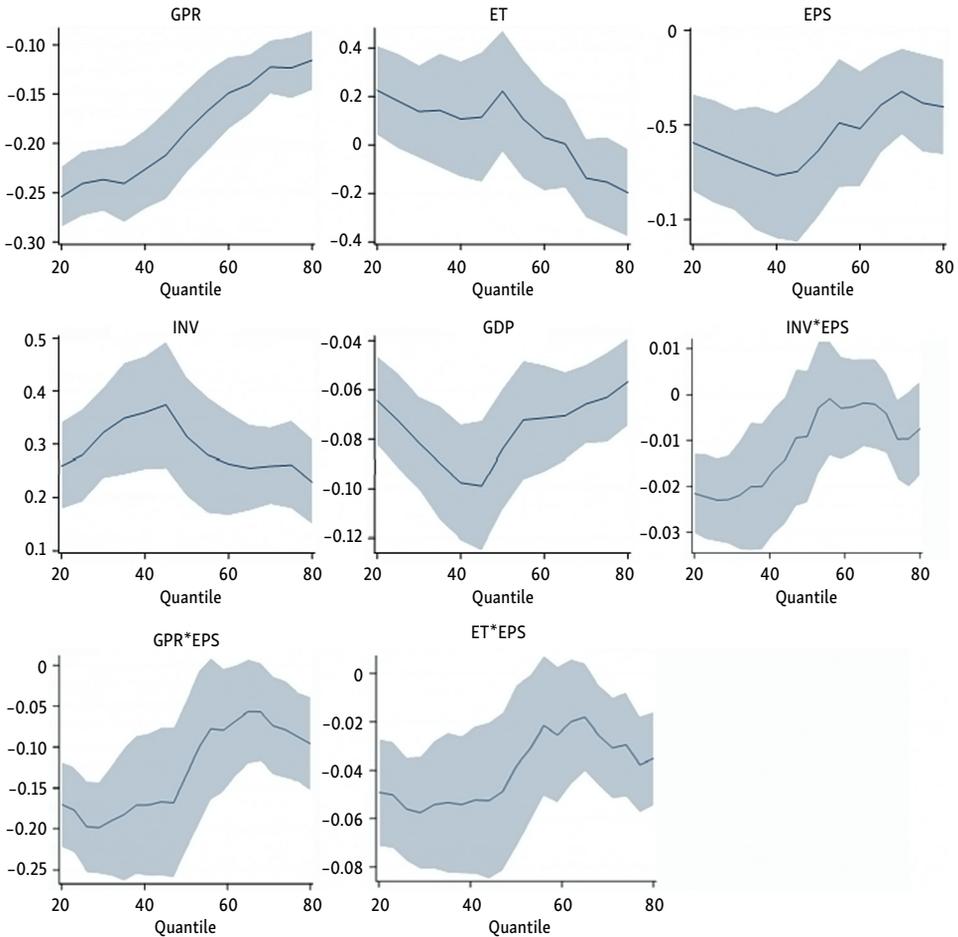
Figure 2. Graphical representation of empirical findings

Further, this study employed QR to confirm the reliability of MMQR findings and to determine any heterogeneity in the associations. The use of QR technique as a robustness check allowed deeper evaluation of the MMQR technique strengthening credibility in the results of enhance the quality of overall study. Table 10 demonstrates that ET, EPS, and INV contribute to lower the CO_2 emissions, whereas, GPR and GDP increase the CO_2 emissions across different quantiles in the sample countries. A significant level of coherence is observed in the findings acquired from MMQR and QR methods. The coefficients of GPR, EPS, ET, INV, and GDP showed similar magnitudes and were statistically significant. The reliability obtained, specifically in terms of the magnitude and direction of the coefficients, highlights the relia-bility of our initial findings in the MMQR model, hence enhancing the previous associations between factors and carbon emissions.

Therefore, from the study findings, it can be argued that the phenomenon of natural resource depletion is mitigated as the country's efforts to enhance productivity while utilizing

Table 10. Quantile regression

Variables	Quantiles			
	20	40	60	80
GPR	0.2600275*** (0.0416138)	0.3596537*** (0.0540844)	0.2635525*** (0.0496172)	0.2295613*** (0.0409591)
ET	−0.2539957*** (0.0156037)	−0.2264174*** (0.0202798)	−0.1488091*** (0.0186047)	−0.115574*** (0.0153582)
EPS	−0.0593041*** (0.0130075)	−0.0767488*** (0.0169056)	−0.0519093*** (0.0155092)	−0.0404088*** (0.0128029)
INV	−0.0643764*** (0.0091774)	−0.0974234*** (0.0119277)	−0.0714356*** (0.0109425)	−0.0567466*** (0.0090331)
GDP	0.2255805** (0.0934388)	0.1073839** (0.12144)	0.0312709** (0.1114094)	−0.1968589** (0.0919688)
INV*EPS	−0.0215009*** (0.0044447)	−0.0183616** (0.0071226)	−0.0037195** (0.0055789)	−0.0074509** (0.0052112)
GPR*EPS	−0.1699827*** (0.0264737)	−0.166139*** (0.0435989)	−0.0854266*** (0.0367619)	−0.0960084*** (0.0293869)
ET*EPS	−0.0491304 (0.0113035)	−0.0471719** (0.0148087)	−0.025149*** (0.0139774)	−0.0351858*** (0.0098587)
_cons	0.8165586*** (0.1278118)	1.043284*** (0.1661137)	1.107002*** (0.1523932)	1.400698*** (0.125801)

limited resources, owing to advancements in current technology and the implementation of stringent environmental policies. These advancements have led to a reduction in environmental degradation, thereby resulting in a decrease in CO_2 emissions. A significant and persistent association has been observed between Economic Growth (EG) and CO_2 emissions. Throughout each stage of economic development, countries strive to increase their output at all costs. Consequently, the emphasis on safeguarding the environment is relegated to a subservient level. The correlation between economic activities and the increase in CO_2 emissions becomes less evident as countries adhere to more environmentally sustainable policies and adopt advanced technologies.

4.10. Panel granger causality test analysis

Table 11 demonstrates the causality analysis results, the empirical findings indicate that the GPR, ET, and GDP have a bidirectional causal association with CO_2 emission, whereas, EPS and INV has a unidirectional causal relationship with CO_2 emissions.

This implies that changes in these independent parameters can be employed as indications of anticipated variations in CO_2 emissions, emphasizing their potential prominence as crucial determinants affecting CO_2 emissions in EU countries.

Table 11. Dumitrescu and Hurlin (2012) causality test

Causality Directions	W-Stat	Z-Stat	Direction	Probability
$CO_2 \approx GPR$	4.9588	10.093	$CO_2 \rightleftarrows GPR$	0.0000
$GPR \approx CO_2$	1.9725	2.4794		0.0132
$CO_2 \approx ET$	10.3801	23.9146	$CO_2 \rightleftarrows ET$	0.0000
$ET \approx CO_2$	2.5945	4.0653		0.0000
$CO_2 \approx EPS$	1.3178	0.8103	$CO_2 \rightarrow EPS$	0.4178
$EPS \approx CO_2$	1.725	1.8483		0.0646
$CO_2 \approx INV$	6.092	12.9822	$CO_2 \rightarrow INV$	0.0000
$INV \approx CO_2$	0.7953	−0.5219		0.6017
$CO_2 \approx GDP$	2.8989	4.8412	$CO_2 \rightleftarrows GDP$	0.0000
$GDP \approx CO_2$	2.4567	3.7139		0.0002
$CO_2 \approx INV\,*EPS$	2.1015	2.8084		0.0050
$INV\,*EPS \approx CO_2$	1.4197	1.0701	$CO_2 \rightarrow INV\,*EPS$	0.2846
$CO_2 \approx GPR*EPS$	2.2371	3.1541		0.0016
$GPR*EPS \approx CO_2$	1.7251	1.8487	$CO_2 \rightleftarrows GPR*EPS$	0.0645
$CO_2 \approx ET*EPS$	1.8793	2.2417		0.0250
$ET*EPS \approx CO_2$	1.7070	1.8024	$CO_2 \rightleftarrows ET*EPS$	0.0715

5. Conclusions and policy implications

5.1. Conclusions

This research contributes to the growing body of literature that examines the geopolitical repercussions on a sustainable environment. The GPR has recently been acknowledged as a significant factor persuading environmental quality. However, there is currently a lack of consensus among scholars regarding the extent of GPR's impact on CO_2 emissions. Therefore, the present study used an empirical analysis to examine the influence of GPR, ET, EPS, and INV on CO_2 emissions in the dataset from 1990 to 2020 for 13 EU countries by employing the DOLS, FMOLS, CCR, and MMQR techniques. The study findings show that GPR and EG are positively and significantly associated with environmental degradation. However, EPS, ET, and INV are negatively associated with CO_2 emissions. This depicts that switching to renewable energy sources, implementation of strict environmental policies and adoption of innovative technologies help to mitigate the detrimental impacts of CO_2 emissions in EU countries. The findings of ET and INV confirm Porter's hypothesis which indicates that EPS fosters the use of innovative technologies and consequently improves environmental sustainability. Further, combined effects of GPR*EPS, INV*EPS, and ET*EPS contributes to lower CO_2 emissions and improves the environmental quality. This posits that EPS play moderating role in enhancing the environmental quality in sample nations.

Furthermore, the findings of current study suggests that the domain of low-carbon development, involving transition to renewable energy sources and innovative technologies, has significant potential for fostering future collaboration. There exists a significant opportunity to enhance global efforts, and in contrast to other economies, the European Union has made

significant progress in its climate and energy transition. SDGs and Paris Agreement targets entail a commitment by countries to significantly reduce carbon and other Greenhouse Gas (GHG) emissions to SDG 7 & 13 in the future, consequently requiring a fundamental transformation of their economies and societies.

Moreover, our findings suggest that the present European Commission is striving to initiate an unprecedented phase of decarbonization within the European Union, while also striving to assume a renewed position for driving climate action. The domain of low-carbon development, comprising renewable and clean energy technologies, exhibits significant potential for fostering future collaboration. There exists a significant opportunity to enhance global efforts, and the European Union (EU) has accomplished substantial advancement in its climate and ET when compared to other economies on a global level. As an initial measure in the ET, this has the potential to create synergies with the extraction of oil and gas, thereby boosting the accessibility of these non-renewable resources for international trade. Moreover, renewable energy demonstrates growing cost benefits, has gained global recognition as a significant energy source, and can be integrated with existing initiatives and strategies for economic diversification. Considering the current prominence of the European Green Deal within EU politics, it is imperative to examine the key factors that the policymakers should consider throughout the formulation and execution of the European Green Deal's external dimensions.

5.2. Policy implications

Based on study findings, policymakers should consider various significant factors. During time of higher GPR, it is crucial to implement specific policies to reduce CO_2 emissions. It may include implementation of strict environmental regulations and provision of subsidies and incentives aimed at decreasing CO_2 emissions. To address the negative impact of GPR on the environment, governments should emphasize fostering a sustainable environment for investment in innovative technologies. Furthermore, in response to the increasing GPR, countries possess the ability to proactively regulate the allocation of financial resources towards environmentally friendly sectors and foster the transition and adoption of RE sources. Moreover, EU countries must enhance their investments in INV and R&D to enhance the level of international trade and the advanced technologies of exported goods. Countries, particularly those with limited resources in R&D and knowledge accumulation, should vigorously promote international collaboration in technology and R&D initiatives. Thirdly, the current study provides substantial implications for EU economies intent on lowering CO_2 emissions and transforming into a carbon-neutral economy. The findings imply that strict environmental policies can considerably curb emissions, however, these may have detrimental economic repercussions. Thus, policymakers should rigorously assess the potential benefits and constraints of implementing strict environmental rules. Finally, based on the findings derived from current analyses of the diverse impacts of GPR on CO_2 emissions, it is recommended that regional authorities expedite the process of transitioning their economies towards environmentally sustainable practices. Employ fiscal and financial measures, such as taxation, to enhance the efficient allocation of resources, expedite the process of technological advancement, and mitigate the expenses associated with emission reduction across all sectors of society. Encourage the development of technological advancement capabilities in businesses, to mitigate the adverse effects of greenhouse gas emissions on environmental sustainability.

5.3. Limitations of the study

The present study is subject to numerous limitations. First, the current study solely focuses on the effect of GPR, ET, EPS, INV, and EG on CO_2 emissions. Future research can investigate further determinants of CO_2 emissions, including technological innovation, globalization, R&D, etc. A more comprehensive insight of the determinants of CO_2 emissions can be achieved. The study used CO_2 emissions as proxy for environmental quality, future research can use GHG emissions, Load capacity factor or carbon footprints to measure environmental quality. Further, this study has been restricted by the availability of data, leading us to solely utilize data from 13 European Union (EU) countries from 1990 to 2020. Future research can focus on other countries, like G20, OECD, and BRICS countries, and may compare with EU countries and expand the data span. The current study employed DOLS, FMOLS, and CCR approaches to capture the long-term effect of the selected variables, future research may employ novel techniques such as CS-ARDL, AMG, CCEMG, and PMG estimators to capture the long and short-run impact of the explanatory variables on the explained variable. Additionally, a study examining the effects of GPR on the quantity of CO_2 emissions at the corporate level could be a topic of considerable interest.

Disclosure statement

The authors declare no competing interests.

Data availability statement

The data for analysis for the current study is collected from the World Bank Indicator, OECD Statistics and International Court Risk Guide (ICRG). Data will be made available upon request.

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APPENDIX

Table A1. List of sample countries

Spain	Italy	Portugal	Finland	Austria
Germany	Ireland	Poland	Netherlands	
France	Denmark	Sweden	Belgium	