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Strategy towards sustainable energy transition: The effect of environmental governance, economic complexity and geopolitics

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ABSTRACT

The Paris Agreement and COP27 have been actively working towards a transition to clean energy (SDG-7) and the restoration of the green environment (SDG-13). Therefore, this study was situated within a comprehensive policy framework. This study aims to investigate the effects of environmental governance and economic complexity on energy transition in 20 OECD countries selected for analysis from 1990 to 2021. This study employs the novel MMQR model to account for slope heterogeneity and cross-sectional dependency. Additionally, an asymmetric analysis was conducted to examine the mediating and moderating roles of geopolitical risk in the relationship between environmental governance, economic complexity, and energy transition. The primary findings of this study indicate that (1) environmental governance and economic complexity have a stimulating effect on energy transition at different levels of quantiles. Strict environmental policies have played a critical role in the transition to clean energy. Furthermore, the interaction between environmental governance and geopolitical factors negatively impacts energy transition at various quantiles; (2) economic complexity demonstrates a positive association with energy transition, as countries with high economic complexity possess the necessary resources, capabilities, and resilience to effectively address the challenges and seize the opportunities associated with transitioning to cleaner and more sustainable energy sources. However, the interaction of economic complexity with geopolitics transforms the positive influence of geopolitics into a negative influence on energy transition. The novel nonparametric panel Granger causality test establishes a significant causal relationship, revealing that environmental governance and economic complexity can support energy transition by creating a favorable environment for clean energy adoption, fostering innovation, facilitating effective planning and implementation, enhancing economic resilience, and promoting international collaboration.

1. Introduction

Energy transition and decarbonization are vital for ensuring environmental stability and fostering sustainable growth [1,2]. The Paris Agreement, a significant international initiative ratified by 195 countries in 2015, aims to address global warming and mitigate the adverse effects of climate change [3]. This establishes the goals of reducing global greenhouse gas emissions and adapting to the effects of climate change. Despite their importance, progress towards these goals has been sluggish, and environmental degradation remains a pressing global issue [4]. Various conferences of the United Nations Climate Change, known as COP26, were held in Glasgow from October 31 to November 13, 2021. The main objective of COP26 is to achieve agreement in addressing climate change [5,6]. COP26 has set several goals, such as achieving global net-zero emissions by the mid-century, limiting the global temperature increase to 1.5 °C, protecting natural habitats and

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communities, mobilizing sustainable finance, and promoting collaboration [7]. Most recently, COP27, held in Egypt in November, has served as a platform for nations to collectively acknowledge climate change as a global issue. The conference aimed to establish new strategies and initiatives to fortify the application of the Paris Agreement, with a focus on fostering actions that can drive towards a sustainable future, pigeonholed by a greener and carbon-free environment [8]. Governments and the private sector can contribute to these goals by investing in renewable energy projects and clean energy technologies, which will provide essential resources for clean energy transition [9,10]. Progress in meeting the Sustainable Development Goals (SDGs) specific to affordable energy (Goal 7) and climate action (Goal 13) hinges on the sustained dedication of the international community, notably by technologically sophisticated OECD member states [11]. The 27th Conference of the Parties (COP27) underscored the pivotal role played by Organization for Economic Co-operation and Development (OECD) countries in spearheading global environmental conservation initiatives [8,12].

The transition to sustainable energy is crucial for mitigating climate change, as global warming poses a significant threat to the planet. Therefore, moving from fossil fuels to renewable energy sources has become imperative. This study aims to understand how to effectively make this transition, while considering the complex interplay between governance, economics, and geopolitics. Effective environmental governance is essential for a successful energy transition, as it facilitates or hinders the shift to sustainable energy. This study examines how laws, policies, and institutional frameworks can guide and accelerate this transition. Understanding the role of governance in guiding and accelerating this transition is vital.

The shift towards sustainable energy has profound economic implications, affecting industries, job markets, and overall economic health. This research explores how complex economic factors, such as market dynamics, investment in green technology, and the impact on traditional energy sectors, play a role in energy transition. Energy is a key factor in geopolitics, and the move towards sustainable energy can alter global power dynamics, affecting everything from international relations to national security. This research is vital for understanding how geopolitical considerations will shape and be shaped by the global move towards sustainable energy. The urgency of addressing environmental issues and the global nature of climate change makes this research universally relevant. It offers insights that could be beneficial for countries at different stages of development and with varying resource levels. This research can lead to innovative energy solutions and encourage international collaboration. Understanding the interconnectedness of environmental governance, economic complexity, and geopolitics can foster global cooperation in the pursuit of a sustainable future.

Energy transition involves decarbonizing the energy sector by minimizing or eliminating reliance on carbon-rich energy sources, such as coal, oil, and natural gas [9]. The transition towards clean energy resources is necessary to diminish our reliance on fossil fuels, which are major contributors to carbon emissions and climate change. Hence, it is crucial for businesses and policymakers to effectively allocate their resources toward transitioning energy consumption away from fossil fuel consumption. This can be achieved by investing in the transformation and diversification of energy sources towards renewables [6]. Renewable energy sources release negligible CO2 emissions, rendering them highly efficient in curtailing worldwide emissions and decelerating global warming. It is important for businesses and policymakers to grasp the variables that drive the shift toward eco-friendly energy and ecological equilibrium, aiming to alleviate the adverse consequences of climate change.

This research adopts a comprehensive approach by analyzing the interplay between environmental governance, economic complexity, and geopolitics in the context of sustainable energy transition. Unlike many existing studies that focus on each factor individually, this study integrates these elements to provide a more in-depth understanding of the dynamics that influence energy transition. By selecting OECD countries as case studies, this study distinguishes itself from others that center on individual countries or specific regions. This diversified dataset enables cross-country comparisons and the potential discovery of shared trends with global applicability. Emphasis has been placed on geopolitics, which has often been overlooked in similar research. By examining the role of geopolitics, this study contributes significantly to the understanding of the influence of international relations on energy transition strategies. In addition to analyzing the factors affecting sustainable energy transition, this study aims to provide policy recommendations. This practical approach differentiates it from purely theoretical inquiries, making it a valuable resource for policymakers and stakeholders to promote sustainable energy practices. This study acknowledges the global relevance of OECD countries and aspires to deliver insights that extend beyond this context, enriching the global discourse on energy transition and its implications for a sustainable future.

The utilization of the environmental policy stringency index is preferred over Green Growth Measures, as it encompasses a broader range of priority indicators related to renewable energy production and energy conservation. This index provides a more comprehensive and reliable assessment of environmental policy effectiveness [13]. Industrialized OECD economies have collaboratively formulated a policy framework to address ecological degradation stemming from emissions. Advancements in renewable energy have played a crucial role in mitigating ecological concerns. The primary aim of such policy frameworks is to enhance environmental conditions through a mix of financial encouragement and disincentives, such as taxation, to stimulate a shift toward more eco-friendly energy options. To this end, the Ecological Rigor Index has been formulated to assess the efficacy of regulatory measures taken by diverse jurisdictions in advancing sustainable environmental conduct. Additionally, this index serves as an analytical tool for understanding the impact of rigorous regulations on corporate competitiveness and technological advancement [14,15]. According to Ref. [16], stringent environmental policies aim to internalize the costs associated with ecologically harmful behavior at the firm or household level. This is achieved by implementing measures such as carbon taxes, which incentivize the shift towards environmentally friendly goods and services while discouraging unsustainable production and consumption [17,18]. The current urgency lies in shifting our focus towards stringent environmental policies and regulations to enhance ecological quality. It is crucial to move beyond merely identifying the factors that degrade the environment and prioritizing the execution of effective environmental regulations that lessen the harmful impacts of pollution. This proactive approach is essential for addressing the pressing environmental challenges that we face today [16,19,20].

The Economic Complexity Index (ECI) has garnered considerable interest among researchers and policymakers owing to its ability to explain a greater degree of difference in economic per capita income and economic development than other commonly used variables, such as governance, institutional quality, education, and competitiveness [21]. The Economic Complexity Index (ECI), proposed by Ref. [22], serves as a measure of structural transformation in an economy. It represents the attributes, expertise, technical know-how, knowledge, and skills of an economy, which facilitate the development of higher efficiency capabilities [23]. ECI is associated with increased productivity [24] and the ability to create more sophisticated services and products [25]. Economic progress, continuous adaptation, innovation [26,27], and the adoption of emerging technologies are essential. These measures contribute to ongoing learning within the economy, leading to improved outcomes [28,29] while mitigating risks and minimizing financial and operational vulnerabilities [30].

Geopolitical risk presents considerable obstacles to the adoption of clean energy and the maintenance of environmental equilibrium, particularly concerning supply factors. Elements such as armed conflicts, terrorist activities, and military engagements exacerbate capital expenditure for private enterprises, thereby displacing external investments and necessitating greater financial input from governmental entities [31]. Nevertheless, geopolitical risks also reduce the management competence of state resources [32]. On the other hand, on the demand side during periods of geopolitical risk, individuals tend to allocate less spending towards renewable energy due to rising domestic costs and the need to prioritize other essential expenses [33]. Recent events such as the Russia-Ukraine War have highlighted the influence of geopolitical risks on energy infrastructure and price fluctuations[34], which can ultimately influence the feasibility of renewable energy investments as substitutes for fossil fuels. The nexus between geopolitical risks and clean energy can vary, with both negative and positive impacts depending on factors such as the extent of dependence on specific energy sources. assess the validity of these hypotheses, we can consider employing new GPR indices of geopolitical risk. The role of political dynamics has received less attention than other factors [35–37]. Implementing and sustaining transformative energy procedures, which often challenge recognized sectors and entail substantial costs, requires substantial political sustenance [38]. Despite the general consensus that ideological barriers, rather than systematic or economic barriers, are the main obstacles to transitioning towards cleaner energy, there remains a pressing need for tax structures that incentivize low-emission energy production. Specifically, targeting fossil fuels such as coal, oil, and natural gas with specialized taxation can improve environmental quality and boost economic performance, particularly when the tax scheme is revenue-neutral.

OECD countries collectively account for a substantial portion of global energy consumption and greenhouse gas emissions, making their experience with sustainable energy transitions valuable for other regions and countries worldwide. With established environmental governance structures and regulations, analyzing these countries allows for a nuanced assessment of the effectiveness of these mechanisms in facilitating energy transition. OECD nations are known for their diverse and complex economies, which can influence their ability to transition towards sustainable energy sources and technologies. By studying these countries, we can investigate how economic complexity impacts the pace and success of sustainable energy transitions. OECD countries typically have reliable data collection and reporting systems, making it easier to gather data on environmental, economic, and energy-related variables. Data availability is crucial for conducting empirical research and drawing meaningful conclusions regarding the effects of various factors on sustainable energy transition. Additionally, studying OECD nations allows for an examination of how geopolitical factors impact energy policies and choices, including international collaborations and negotiations related to energy and climate change.

The main objective of this research project is to scrutinize the intricate interplay between environmental governance, economic complexity, and energy transition in the context of 20 OECD countries selected from 1990 to 2021. This study specifically investigates the Dynamic Effects of environmental governance and economic complexity on the shift toward clean energy. This entails examining the roles that these factors play in facilitating or hindering the transition toward more sustainable energy sources. To overcome the limitations of traditional regression models, the study employs the Method of Moment Quantile Regression (MMQR) model. This advanced statistical technique addresses issues of slope heterogeneity and cross-sectional dependency, enabling a more refined and precise analysis of the data. A crucial aspect of this research is to explore the moderating and mediating roles of geopolitical risk. This involves assessing the influence of geopolitical factors on the relationship between environmental governance, economic complexity, and energy transition. By employing the MMQR model, this study aims to uncover the varying effects of these relationships across different levels or quantiles. This approach allows for a more detailed understanding of how environmental governance and economic complexity impact energy transitions at various points in the distribution. The study not only focuses on average effects, but also aims to provide a nuanced understanding of the relationships between the variables of interest.

This study makes a significant contribution to the empirical literature by offering valuable additions. It is unique in that it investigates the impact of environmental governance and economic complexity moderated by geopolitical risk on the transition to sustainable energy and environmental stability. This study employs a panel dataset from 1990 to 2021 for OECD countries and examines geopolitical risks alongside other possible drivers affecting energy transition and environmental resilience. To the best of our knowledge, this is the first study to assess the compounded effects of geopolitical risks, economic complexity, and environmental governance on these areas of concern. A recent index of geopolitical risk was created by Ref. [39] for OECD economies. This distinctiveness in our research yields disparate outcomes compared to previous studies, as the majority of them uncovered a positive nexus between geopolitical risks and a shift towards clean energy sources. However, our study reveals a contrasting revelation: geopolitical risks diminish the impetus for energy transition and cast a shadow over climate change mitigation policies. Furthermore, escalating geological risk compounds the challenge, undermining both energy transition efforts and environmental stability. Second, the statistical technique employed is the “Methods of the Moment of Quantile Regression” (MMQR), which was proposed by Ref. [40]. The technique under consideration can yield insightful results by linking predictor variables to quantiles of the criterion variable. It exhibits robustness in commerce, even in the presence of outliers, normality, heterogeneity, and endogeneity. Moreover, the study employs robust Bootstrap Quantile Regressions to ensure the reliability of the findings. This approach involves resampling the original sample and estimating the values for each quantile to provide an efficient estimate. Furthermore, this study conducts a novel analysis of the causal relationship between environmental governance, economic complexity, geopolitical risk, energy transition, and environmental stability in OECD economies. As a result, this study contributes valid and original insights to both the empirical and theoretical literature.

The organizational structure of this manuscript is as follows: The second section provides a comprehensive literature review of the research analysis. The third section documents the model development and data measurement of the study. The fourth section outlines the econometric strategies. The fifth part presents the preliminary results of this research. The sixth part discusses these results and their economic implications. Finally, in the conclusion of the seventh section, we summarize these findings and delve into their policy implications.

2. Literature review

This section presents empirical evidence pertaining to the study factors, their interrelationships, and the key aspects that contribute to a comprehensive analysis. This study provides original insights and findings that contribute to the understanding and evaluation of this research topic.

2.1. Environmental governance on energy transition

The introduction of OECD environmental policy stringency serves as a global reference point for countries to evaluate their progress [16]. Climate governance has become a distinct field of study and policy, focusing on advancing the theoretical understanding of environmental justice and sustainability dynamics [5,41]. Stricter environmental regulations have been linked to greater productivity in both industrial and thermal power plant sectors, both at the national level and among leading economic nations [42]. Moreover, the enactment of laws has played a vital role in driving climate change policies and facilitating the transition towards a sustainable, green economy. Additionally, policy-oriented elements such as alternative social values and agendas have been instrumental in this process [43,44].

The existing literature has extensively examined different aspects of economic and governance dynamics. is difficult to replicate. World organizations emphasize the importance of transitioning to cleaner energy while prioritizing sustainable development goals. The results of the NCA model suggest that energy consumption is a necessary condition for a reduced ecological footprint. On the other hand, the fsQCA model demonstrates that low GDP is a prerequisite for a decreased ecological footprint. Additionally, the fsQCA model identifies five combinations of solutions for both increasing and decreasing the ecological footprint [45]. Energy transition and environmental stability are closely linked to achieving economic and environmental stability, ensuring the well-being of communities while minimizing ecological damage. Emerging economies must implement environmental plans that amalgamate economic decisions and environmental concerns [46]. Current environmental issues are primarily attributable to the extensive utilization of fossil fuels and related energy sources, resulting in climate susceptibility. To alleviate the adverse consequences of conventional energy sources, it has been suggested that countries increasingly utilize alternative energy sources [6]. Environmental governance policies have been found to be associated with increased productivity in industrial and thermal power plants, both at the country level and particularly in advanced economies[42].

According to Ref. [47] conducted a study on 20 OECD economies and initiate a long-run equilibrium nexus between environmental restrictions and green innovation, suggesting that strict environmental policies stimulate long-term progress [48] noted that diverse measures of environmental policy stringency used in the literature show significant correlations, incorporating survey-based measures, environmental consequences, and complex policy-based measures [49]. study the connection between stricter environmental policies and an increase in patent applications and total factor productivity (TFP) is significant. Specifically, this increase is most noticeable in the upper ranges of the patent distribution and across all TFP quantiles. This relationship is particularly evident in the near term [50]. suggested that combining stringent regulations with renewable energy leads to greater benefits in carbon emission reduction compared to their separate effects, highlighting the importance of transitioning to renewable energy through strict regulations [11]. reported that the involvement of regional authorities plays a substantial role in facilitating energy transitions. However, the impact of enforcing climate-change laws has yielded mixed outcomes. The findings of this study suggest that corruption negatively impacts environmental quality, as evidenced by three out of the four measures of environmental degradation. However, it has been observed that this adverse effect tends to diminish in scenarios where environmental degradation is already at an advanced stage [51].

2.2. Economic complexity on energy transition

However, the nexus between clean energy and economic complexity has received little empirical attention. The ECI reflects the capacity and capability of an economy and has been identified as a potential solution for pollution alleviation [52]. In essence, it signifies an economy's expansion in terms of high-tech development and action-driven modernization, leading to the creation of timely, unique, and innovative products that are difficult to replicate [53,54]. Recently [55], conducted an in-depth investigation of the scope, significance, theoretical linkage, and application of ECI in various contexts, including innovation, economic development, and geographical considerations. Researchers have examined the relationship between EC and environmental stability. The purpose of this study is to examine the influence of economic complexity on energy transition and environmental stability and the subsequent role of geopolitical risk. The study's findings indicate that in G7 countries, environmental taxes are successful in diminishing emissions. Additionally, as the rate of environmental taxation increases, there is a statistically significant escalation in the impact on traditional energy use, revenues from natural resources, and the consumption of renewable energy [56]. Likewise [57], discovered that in 14 European countries, economic complexity leads to a decline in non-renewable energy consumption while simultaneously promoting an increase in the utilization of clean energy sources. Correspondingly [58], concluded that economic complexity is a significant policy aspect driving energy transition and promoting clean energy demand, with effects observed in G7 and E7 countries. However [59], revealed that economic complexity is associated with a decrease in clean energy consumption across 18 Latin American countries [60]. investigated the effects of income inequality and economic complexity on ecological footprints in 25 countries from 1970 to 2016 using panel quantile regression. The findings indicate that higher economic complexity positively influences the ecological footprint in the 10th and 25th quantiles [61]. also contribute to the literature by examining the impact of economic complexity, defined as the shift towards more advanced and knowledge-driven production, on economic development, the adoption of renewable energy sources, and population growth in relation to carbon emissions. Moreover, [62]; analyzing data gathered from 16 countries in Latin America, this study examines the intricate interplay between human capital and economic complexity, showcasing how this combination affects clean energy consumption and results in diverse outcomes. Quantitative analysis using quantile regression across a comprehensive range of countries revealed that heightened economic complexity leads to enhanced energy efficiency. This improvement is primarily reflected in the reduced energy and carbon intensity [63].

Similarly [64,65], utilized a panel quantile approach to explore the linkage between economic complexity and different proxies for energy variables across different conditional distributions. Globally, economic complexity has hampered energy effectiveness and shifted to clean energy sources. According to recent research, a negative correlation exists between economic complexity and both clean energy consumption and electricity output across all income groups, except for a few instances in which the relationship is either inconsequential or varied [58]. explored the influence of an economic complexity index on green energy using various econometric approaches. These findings suggest that ECI positively influences clean energy adoption. [66,67], examined 23 selected nations and executed a panel quantile econometric approach to analyze the effect of ECI on REN. They discovered an adverse relationship between ECI and REN in the lower quantiles, whereas a positive nexus was evident in the central and higher quantiles. In contrast [68], who engrossed on the GCC states, revealed a negative impact of EC on RE. Furthermore, previous studies overlooked the environmental significance of economic complexity in different economies. For instance Ref. [69], suggested that increased economic complexity leads to reduced inclusive carbon emissions [25,70]. identified that nations exhibiting elevated economic complexity witness a more rapid reduction in emissions, which is attributed to variations in energy efficiency. Nonetheless, heightened economic complexity may also result in heightened ecological degradation driven by augmented energy production. Similarly [71,72], show that economic complexity, renewable energy consumption, trade openness, FDI, and institutional quality enhance economic growth.

3. Model development and data measurement

3.1. Model specification

The study followed [1,73–77] to study the effect of environmental governance, economic complexity, and geopolitical risk on energy transition. We constructed a subsequent multivariate framework, drawing inspiration from prior researchers' contributions, to assess the potential influence of environmental governance, economic complexity, and geopolitical risk on energy transition:

$$LnET_{it} = f\left(lnEGOV_{it}, LnEC_{it}, LnGPR_{it}, LnGI_{it}, LnGDP_{it}\right) \tag{1}$$

where ET, EGOV, EC, GPR, GI, and GDP denote energy transition, environmental governance, economic complexity, geopolitics, green innovation, and economic growth, respectively. While *i* and *t* indicates the cross sections and *t* period (1990–2021). Next, incorporating the interaction term between geopolitical risk, environmental governance, and the economic complexity effect on the dependent variables into equation (2-3) shows the economic functions of energy transition.

$$LnET_{it} = f\left(lnEGOV_{it}, LnEC_{it}, LnGPR_{it}, LnGI_{it,}LnGDP_{it}, lnEGOV_{it} \divideontimes LnGPR_{it}\right) \tag{3}$$

$$LnET_{it} = f\left(lnEGOV_{it}, LnEC_{it}, LnGPR_{it}, LnGI_{it,}LnGDP_{it}, LnEC_{it} \divideontimes LnGPR_{it}\right) \tag{4}$$

Where the $\divideontimes$ show the multiplication term define the interactive effect of geopolitical risk and environmental governance, geopolitical risk, economic complexity, $(EGOV \divideontimes GPR)$, $(GPR \divideontimes EC)$ possible effect on energy transition. Therefore, we estimate four basic equations: environmental governance, economic complexity, and the interaction term between environmental governance and geopolitical risk and economic complexity and geopolitical risk and its effect on the dependent variables. The four models are expressed as follows

$$LnET_{it} = \vartheta_0 + \vartheta_1 lnEGOV_{it} + \vartheta_2\ LnEC_{it} + \vartheta_3 LnGPR_{it} + \vartheta_4 LnGI_{it} + \vartheta_5 LnGDP_{it} + \vartheta_6 lnEGOV_{it} \divideontimes LnGPR_{it} + \varepsilon_{it} \tag{5}$$

$$LnET_{it} = \vartheta_0 + \vartheta_1 lnEGOV_{it} + \vartheta_2\ LnEC_{it} + \vartheta_3 LnGPR_{it} + + \vartheta_4 LnGI_{it} + \vartheta_5 LnGDP_{it} + \vartheta_6 lnEC_{it} \divideontimes LnGPR_{it} + \varepsilon_{it} \tag{6}$$

In Equations (5) and (6), the error term is represented by ε. The term ε accounts for the unexplained or remaining variability of the dependent variable. It is believed that ε follows an arbitrary distribution with a mean of zero, and incorporating it into the model provides a more accurate portrayal of real-world data scenarios. Table 1 presents comprehensive details regarding the parameters under examination, along with their corresponding units of measurement and data sources. All parameters were logarithmically transformed for analysis.

3.2. Data measurement

Our study examines the effects of environmental governance, economic complexity, and geopolitical risk on energy transitions in OECD countries. The investigation employed panel data from 1990 to 2021. The primary emphasis of this research is on energy transitions, which serve as dependent variables. These variables were assessed in relation to independent factors to determine their impact on the overall outcome. Environmental governance (EGOV), economic complexity (EC), and geopolitical risk (GPR). To ensure conformity with normality assumptions, the data were logarithmically transformed. It is essential to mention that the selection of countries for this analysis is contingent upon data accessibility within the Organization for Economic Co-operation and Development (OECD) nations and is consistent with the timeframe utilized for examination.

Table 1
Abbreviations, definitions, sources, and units of measurement for variables.

Variable	Symbol	Measurement	Source
Energy transition	*ET*	Share of primary energy from renewables	BP Statistical Review of World Energy
Environmental Governance	*EGOV*	Environmental Policy Stringency index	https://stats.oecd.org.
Economic Complexity	*EC*	Index from 0 to 100	https://oec.world/en/rankings/legacy_eci.
Geopolitical Risk	*GPR*	Index	[39]
Green innovation	*GI*	Environment-related technologies growth to percentage of all technologies	https://stats.oecd.org.
Economic Growth	*GDP*	Gross domestic product	WDI

The primary data for the dependent variables were energy transitions. The ET data were obtained from the BP Statistical Review of World Energy. The GPR data used in our analysis (GPR) were created by Ref. [39]. The economic complexity index (ECI) was obtained from the Observatory of Economic Complexity (OEC) for 2022. The complexity of an economy is defined by how a country structures its production capacity and integrates and uses its knowledge [76,78]. It quantifies an economy's knowledge depth and is considered a valuable predictor of both future growth and diverse environmental outcomes. The stringent environmental policy index serves as a proxy for environmental governance and green innovation. It's computed by gauging the growth of environment-related technologies in relation to the overall technology landscape, with data collected accordingly from https://stats.oecd. org/. Based on literature reviews and recent studies [1,74–77]. Table 1 outlines the data specifics: sources, measurements, and symbols. The period selected for analysis, spanning from 1990 to 2021, encompassed a substantial amount of time during which critical developments related to energy transition and relevant factors in OECD economies occurred. This period covers over three decades, during which significant changes in the global energy landscape, international agreements such as the Kyoto Protocol and Paris Agreement, technological advancements, and energy policies have occurred. Furthermore, this timeframe includes several economic and environmental milestones, including the global financial crisis of 2008 and the growing emphasis on sustainability and climate change mitigation. This timeframe allows us to examine the various factors that have influenced energy transition and economic complexity during this era.

Environmental governance is a measure of a country's policies, institutions, and regulations to address environmental concerns, including those related to energy and sustainability [79]. One of the benefits of this index is that it considers country-specific measures to evaluate stringent environmental policies. Additionally, it can be compared internationally with a range of 0–6, where 0 represents no stringency and 6 represents the highest level of stringency. This is a crucial factor in understanding the regulatory environment for energy transition. Environmental governance is widely discussed in environmental studies and policy literature [80]. This has been linked to sustainable development and the success of environmental policies [81]. It is also associated with the Environmental Performance Index (EPI) developed by Yale University. Geopolitical risk is included, as it plays a significant role in shaping a country's energy policies and choices. Factors such as international relations, conflicts, and alliances can impact energy security and decision-making [82]. Geopolitical risk is often discussed in the energy security literature. Authors like Daniel Yergin in "The Prize" and international relations scholars have examined how geopolitical factors influence energy policies. The concept of economic complexity was chosen because it reflects a nation's diversified economic structure, which can impact its ability to transition to sustainable energy sources. A more complex economy is often considered to be better equipped to handle structural changes. The concept of economic complexity, initially proposed by Ref. [22], has gained prominence in the economic and development literature. It is linked to a country's capacity for innovation and adaptation, making it a valuable variable for studying energy transitions [22,83].

4. Econometric strategy

This section describes the application of descriptive statistics, cross-sectional dependence analysis, unit root estimations, cointegration, MMQR, and BSQR. Descriptive statistics encompass mean, median, and range values and variable volatility, which favor standard deviation and accommodate significant range variations. Additionally, the study examines distributional features through skewness and kurtosis, standard metrics ([84], rigorously assesses variable normality, and employs a typical normality test formulation.

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

4.1. Tests for cross-sectional dependence

Preliminary tests are crucial when working with panel data, especially for the assessment of heterogeneous panels, which are more dependent on the characteristics of the panel series, as opposed to homogeneous panels consisting of random- and fixed-effects linear models described by a single slope. In the assessment of heterogeneous panels, the focus is on analyzing the series trends by assessing the variables in each cross-section. To compare the reliability of the combined estimates with the fixed and weighted panel estimates, this study utilized the proposed homogeneity test for slopes [85]. In addition, to address perturbations in the series, a unit root test procedure was employed to identify any nonstationary characteristics. This test was conducted after the slope homogeneity test. The purpose of conducting unit root tests is to prevent spurious regressions [77,86,87]. Panel data inherently exhibit cross-section dependence, and therefore, a cross-section dependence test known as [88,89]. The test is formulated as follows:

$$LM = \sum_{i-1}^{N-1} \sum_{j=i+1}^{N} T_{ij}\widehat{\rho}_{ij}^{2} \rightarrow X^2 \frac{N(N-1)}{2},$$

where X^2 represents the asymptotic circulation for N fixed as T_{ij}, and $\widehat{\rho}_{ij}^{2} \rightarrow \infty$ indicates the correlation coefficients. According to Ref. [85], the LM test proposed by Ref. [89] lacks extensive settings for large numbers of cross-sections (N). To address this limitation [85], provides a consistent formulation of the CD LM test, which is as follows:

$$LM_s = \sqrt{\frac{1}{N(N-1)}} \sum_{i-1}^{N-1} \sum_{j=i+1}^{N} \left(T_{ij}\widehat{\rho}_{ij}^{2} - 1\right) \rightarrow N(0,1)$$

Pesaran (2004) recommended that the dimensions of the panel dataset satisfy $T_{ij} \rightarrow \infty$ and $N \rightarrow \infty$ In addition, to address the issue of size distortion in LM and LMs tests, Pesaran (2004) proposed unconventional statistics constructed from the pairwise average correlation coefficients $\widehat{\rho}_{ij}^{2}$. These unconventional statistics provide an alternative approach for addressing the size distortion problem.

$$CD_{\rho} = \sqrt{\frac{2}{N(N-1)}} \sum_{i-1}^{N-1} \sum_{j=i+1}^{N} T_{ij}\widehat{\rho}_{ij} \rightarrow N(0,1)$$

Asymptotically, the unconventional statistics based on pairwise average correlation coefficients *bqij* are normally standardized when both T_{ij} and N tend to infinity in any order, as described by Pesaran. For a large panel dataset, Pesaran stated that CD (cross-section dependence) equals zero for all T_{ij} greater than K+1 for all N. Therefore, we use all these cross-sectional dependence tests in the empirical measurement.

4.2. Panel unit root test with cross-sectional dependence

Based on the findings of [87,90], traditional first-generation unit--root tests have been found to be insufficient for handling cross-sectional dependence in panel data analyses. In light of this, our study incorporates second-generation unit-root tests, specifically cross-sectional augmented Dickey–Fuller (CIPS) and Common Correlated Effects (CADF). The CIPS approach was originally proposed by Ref. [91] originally proposed the CIPS approach. These second-generation tests offer improvements over their first-generation counterparts, as they can manage both serial correlation and cross-sectional dependence. If the null hypothesis is rejected based on these tests, it is crucial to employ methodologies suitable for analyzing non-stationary data. In addition to unit-root testing, another element that can impact panel study outcomes is cross-sectional dependence (CSD). In our research, we have employed two CSD tests as recommended by Ref. [92,93]. The CIPS panel unit root test is as follows.

$$\Delta X_{it} = \propto_{it} + \beta_i X_{it-1} + \rho_i T + \sum_{j=1}^{n} \theta_{ij} \Delta X_{i,t-j} + \varepsilon_{it},$$

Where the T denotes the time and Δ is a differenced funcation of X_{it} shows our selected variables, while the $\propto$ shows the divergent intercept.

4.3. Tests for cointegration (westerlund cointegration test)

The next crucial step involves examining the cointegration among the variables. Traditional first-generation cointegration tests can produce skewed outcomes because of their limitations in addressing cross-sectional dependence and accurately capturing long-term associations. To tackle this issue, we employ the cointegration testing methodology introduced by Ref. [94] This method offers two key measures: the Durbin-Hausman (DH) strategy, which encompasses both DH board and DH bunch statistics. These measures are specifically designed to consider cross-sectional dependence and offer a more robust analysis in the presence of stationary regressors. Our analysis differs from conventional cointegration tests in that it employs a unique methodology that incorporates cross-sectional dependence and slope homogeneity, resulting in enhanced accuracy and dependability [94]. framework is based on specific factorial residual models, which further enhances this study. Accordingly [94] present the following factorial residual models:

$$G_t = \frac{1}{N} \sum_{i=1}^{N} \frac{\acute{\alpha}_i}{SE(\acute{\alpha}_i)}$$

$$G_a = \frac{1}{N} \sum_{i=1}^{N} T \frac{\acute{\alpha}_i}{\acute{\alpha}_i(1)}$$

$$P_t = \frac{\acute{\alpha}}{SE(\alpha)}$$

$$P_a = T\alpha$$

where Ga and Gt are the group statistics, and Pa and Pt are the panel statistics.

4.4. Method of moments quantile regression (MMQR)

The central aim of this research is to employ moment quantile regression (MMQR) to scrutinize how various regressors affect the conditional distributions of energy transitions in OECD countries. Quantile regression, initially conceived by Ref. [95] provides insights into how the influence of independent variables varies across quantiles of the dependent variable. This is particularly useful for interpreting the computed slope coefficients, which are affected by the levels of the endogenous variables. This study considers the non-uniform distribution of data, opting for an advanced MMQR technique. Machado and Silva [40] further refined this approach [40]to include panel quantile regression with fixed effects, allowing for the examination of both covariance and conditional heterogeneity among the regressors. The subsequent analysis utilizes an equation to highlight the location-scale variability $[\mathscr{Q}_y(\tau/R)]$:

$$Y_{it} = \varphi_i + \beta R_{it} + (\omega_i + \tau Z_{it}))\mu_{it}$$

Where the φ, β, ω represent the coefficient of our study. While the $(\omega_i + \tau Z_{it}) > 0$ shows the probability appearances which are equal to 1.

Additionally, the notion i reflects the fixed effect in considered estimates. The symbol "i'' represents the fixed effects in the estimated model, which are finite numbers. Additionally, the characteristic function of "R" is denoted by "Z," while the characteristic variation is represented by the symbol "Δ." This can be expressed as follows:

$$Z_\Delta = Z_\Delta(R_{it}), \Delta = 1, 2, 3, \ldots..k.$$

The variable "R_{it}" follows an identical and independent distribution across all cross-sections of the panel at time "t'' considering the previous discussions, reasoning, and equations (1) and (2), we can utilize the following model as a modification of the one proposed by Machado and [40] and also employed by Ref. [77].

$$\mathcal{Q}_y(\partial|R_{it}) = \varphi_i + \omega_i q(\partial) + \beta R_{it} + \tau Z_{it} q(\partial)$$

The "R_{it}" represents a set of exogenous variables, including *EGOV*,*EC*, *and GPR*. The sample quantiles were defined as 0.25, 0.50, 0.75, and 0.90. Therefore, this representation is expressed as follows.

$$min_q \sum_i \sum_i \varphi_i (R_{it} - (\omega_i + Z_{it})q)$$

While the MMQR technique offers precise approximations for specific scales and locations, revealing the outcomes of each quantile, the primary objective of this study was to assess the robustness of the constructed model.

The main goal of this approach is to account for the conditional variation in the dependent variable. In doing so, it seeks to uncover the correlation between factors while considering the unique impact of each factor on the entire distribution [96]. The panel quantile regression with fixed effects, which is capable of uncovering the covariance and conditional heterogeneity of the regressors[73]. However, the MMQR method offers precise approximation thereby scale and location, showcasing the outcomes of each quantile. The primary objective of this study was to assess the robustness of the constructed model. This method is beneficial for more complex models in which it is difficult to determine a likelihood function, which is typically required for quantile regression. It can offer more stable estimates when conventional quantile regression assumptions are not met. Assumptions can be made regarding the error distribution and independence, as well as the intricacy of the model being estimated. The Moments Method in quantile regression operates under specific assumptions, which differ from those of traditional regression. It assumes a linear connection between the predictors and conditional quantiles of the response variable, which is crucial for accurate estimates. This method also assumes that errors across different observations are unrelated, which is essential to avoid distorting the accuracy of standard error estimates. Additionally, it assumes that the spread of the residuals is consistent at each quantile level, which is necessary to ensure the reliability of the hypothesis tests because of the affected standard errors. These assumptions are vital to the validity and reliability of a model's estimates.

The CIPS test may be sensitive to structural breaks, where the relationships between variables change abruptly. Detecting and accounting for these breaks is crucial for an accurate analysis. The Westerlund panel co-integration test assumes no endogeneity, but it is common. Failure to address endogeneity can lead to biased cointegration results. Similarly, the Westerlund test assumes cross-sectional independence; however, if it exists, it can lead to incorrect co-integration conclusions.

In addition to non-parametric assessments, this study incorporates parametric robustness tests to validate the findings of the study in addition to non-parametric evaluations, the current study incorporates parametric robustness assessments. Specifically, we employed the robust least-squares technique, which yields the mean coefficient values for the included variables. We examined robustness using the Bootstrap Quantile Regression (BSQR) strategy. This alternative approach serves as a tool for scrutinizing confidence intervals. One of its strengths is its capability to bypass the need for a parametric assumption of an asymptotically normal distribution achieved by data resampling. Using algorithmic methods, the BSQR evaluates the sampling distribution inherent in the model under investigation, thereby offering dependable estimation procedures and revealing empirically substantiated results, as outlined by Ref. [97]. The figure-1 explain this econometric strategy. Bootstrap Quantile Regression (BSQR) is a useful method for quantile regression coefficient estimation and its standard errors. Despite its benefits, such as handling non-normal and heteroscedastic data, BSQR has certain limitations and assumptions that should be considered. BSQR assumes that the original dataset is a representative sample of the population and that the observations are independent. In panel or time-series data, this assumption may not hold, leading to biased results. Moreover, BSQR assumes that the data are stationary, meaning that the statistical properties do not change over time.

We used the econometric software Stata 17.0. Specifically, we employed a range of Stata commands, including sum, xthst, xtcips, xtcointtest Westerlund, and mmqreg. These commands were instrumental in conducting preliminary tests and model estimations.

5. Preliminary results

5.1. Descriptive statistics

Table 2 presents the descriptive statistics, emphasizing the positive mean, median, and range of observations. Specifically, the variables EGOV, EC, and GPR show a steady progression in tandem with the transition towards clean energy and the reduction of carbon emissions in the economies of the (OECD). The range of values demonstrated a considerable degree of variability, encompassing a broad array of disparate extremes. To evaluate the normality of the variables, skewness and kurtosis metrics were utilized. The results indicated non-normality, as the statistical values deviated from their critical values. Given the potential estimation bias associated with non-normality, this study employed a comprehensive normality testing measure. The results demonstrate that ET, EGOV, EC, GPR, and GDP have significant statistical values at the 1% level, leading to the rejection of the null hypothesis of a normal data distribution.

5.2. Cross sectional dependency test and slope heterogeneity

In panel data analysis, assessing cross-sectional dependency (CD) and slope heterogeneity (SLH) is crucial because of their potential to breach the independence assumption between observations. This breach

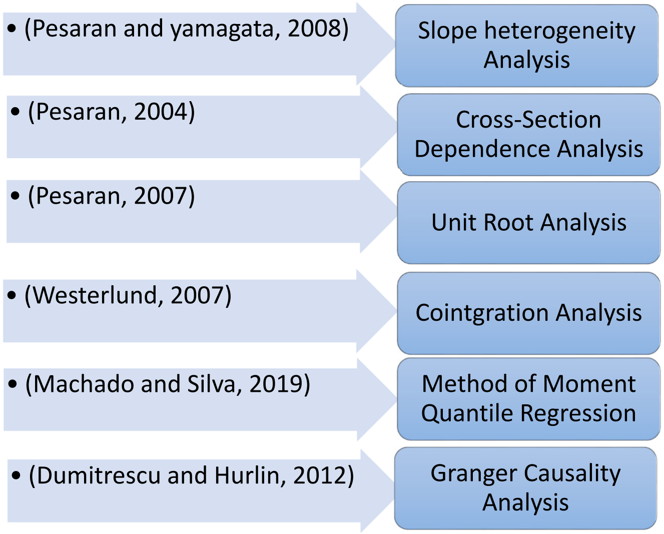

Fig. 1. Methodology design.

Table 2
Descriptive statistics.

	ET	EGOV	EC	GPR	GI	GDP
Mean	10.164	2.269	1.110	0.279	0.957	11.802
Median	4.299	2.388	1.223	0.081	0.965	11.731
Maximum	97.429	4.888	2.624	4.678	1.411	12.991
Minimum	0.560	0.166	−0.842	0.003	0.480	10.880
Std. Dev.	19.473	1.039	0.760	0.626	0.152	0.451
Skewness	3.690	−0.007	−0.318	4.101	0.060	0.186
Kurtosis	15.779	2.025	2.295	20.473	2.893	2.020
Jarque-Bera	5635.793	24.569	23.335	9641.372	0.678	28.395
Probability	0.000	0.000	0.000	0.000	0.712	0.000

Note: ET: Energy transition, EGOV: Environmental governance; EC: economic complexity; GPR: geopolitical risk index; GI, Green innovation; GDP: Economic growth Source: See Table 1.

can result in erroneous standard errors and misleading conclusions [75, 87]. The CD test results are presented in Table 3. The assessments are designed to examine the null hypothesis positing that all variables operate independently across different cross-sections. Across all four tests, the test statistics displayed statistical significance, prompting rejection of the null hypothesis. This result highlights the existence of cross-sectional interdependencies within the studied variables, indicating a prevalent economic singularity that affects variables across the 20 OECD economies. For instance, when a country or region experiences geopolitical conflicts, they can reverberate across other countries and regions, thereby affecting their geopolitical standing. Such outcomes align with expectations in a geopolitical risk scenario. The identification of cross-sectional dependence holds significant implications, which necessitates the application of advanced unit-root tests, such as the CIPS panel unit-root assessment, along with the exploration of models that focus on long-term relationships.

Furthermore, in Table 4 the results of the slope heterogeneity test are presented. This test firmly reinforces the rejection of the null hypothesis of a uniform slope, affirming the presence of diverse slope coefficients across all three models.

5.3. Cross-sectionally dependent panel unit root test

The existence of cross-sectional dependence (CSD), which assesses stationarity properties, becomes pivotal as the adequacy of first-generation panel stationary tests is restricted. Thus, second-generation stationary tests were employed to ascertain the stationarity attributes of the variables; the results are summarized in Table 5. Based on these conclusions, it is deduced that the variables exhibit diverse orders, either I (1) or I (0), rendering them appropriate for extended panel data analyses. Specifically, the energy transition (ET) initially manifests non-stationarity at the level but achieves stationarity after differencing. Conversely, variables such as environmental governance, economic complexity, and geopolitical risks are observed to be stationary. As a result, the null hypothesis of non-stationarity was rejected, confirming the stationarity of all variables. This discovery establishes a robust foundation for estimating the long-term nexus between the investigated variables.

Table 4
Slope heterogeneity test.

	Model: ET		
	$Model - 1$	$Model - 2$	$Model - 3$
Delta	18.787	15.690	15.976
$P - value$	[0.000]	[0.000]	[0.000]
Adj.Delta	21.347	18.211	18.542
$P - value$	[0.000]	[0.000]	[0.000]

Table 5
CIPS unit root test.

Variables	I (0)	I (1)
ET		−5.663***
EGOV	−3.180***	
EC	−2.069***	
GPR	−3.344***	
GI	−3.447***	
GDP		−4.429***

Note: ***p-value<0.01.

5.4. Tests for cointegration

Given the varied integration orders of the variables, it is essential to perform a cointegration test to ascertain the enduring nexus between the dependent and independent variables. Prior to framing the energy transition and carbon emissions function within a long-term framework, it is pivotal to establish the existence of cointegration among the variables. With stationarity confirmed through unit root tests, the dataset becomes appropriate for examining potential cointegration among variables [94,98]. Given the challenge of cross-section dependence (CD), applying second-generation panel cointegration estimation methods is essential because first-generation approaches fail to address the CD issue. Hence, we employ the cointegration technique introduced by Ref. [94] which offers four test statistics (Pa, Pt, Ga, and Gt) under the null hypothesis of no cointegrating association among the variables of interest. The approach used in this study relies on bootstrapping techniques to evaluate statistical significance, while also addressing concerns related to conditional heteroscedasticity through multiple iterations of the test. Table 6 presents the findings related to

Table 6
[94] Bootstrap panel cointegration.

	Energy transition		
	$Model - 1$	$Model - 2$	$Model - 3$
Gt	−1.977	−1.750	−1.508
Ga	−7.305	−5.923	−4.498
Pt	−11.942***	−8.620***	−10.499***
Pa	−9.323***	−5.814***	−7.079***

Note: In the Westerlund ([94] panel cointegration procedure, the null hypothesis assumes no cointegration. The p-values reported in Table 6 represent one-sided tests based on a normal distribution. In addition, a robust p-value was calculated by performing 500 repetitions of a one-sided test using the self-help method. The estimates presented in Table 6 were derived from the analyses conducted by the authors.

Table 3
Cross sectional dependency test.

Test	ET	EGOV	EC	GPR	GI	GDP
Breusch-Pagan LM	2073.146***	4801.806***	1973.913***	829.077***	2429.550***	4907.019***
Pesaran scaled LM	96.603***	236.580***	91.512***	32.783***	114.886***	241.9780***
Bias-corrected scaled LM	96.280***	236.258***	91.190***	32.461***	114.563***	241.6554***
Pesaran CD	21.525***	68.255***	23.557***	21.627***	43.148***	69.15157***

Note: ***p-value<0.01. Source: Authors' calculations.

cointegration. Interestingly, the null hypothesis, which posits the absence of cointegration, is consistently dismissed in all scenarios, ranging from Models 1 to 6. This suggests that cointegration exists between the variables examined in both models. Given these results, it is viable to employ long-term econometric models for a more nuanced understanding of the direction and magnitude of the relationships among the variables under consideration. The subsequent analysis is dedicated to achieving this goal by delving into the long-term linkages between variables. Additional estimations can offer more nuanced insights. Consequently, Tables 7and8 present the results of MMQR, while Figs. 2–4 offer graphical depictions of MMQR and BSQR.

6. Empirical results and discussion

6.1. Results of method of moments of quantile regression

To confirm the long-term cointegration relationship among the variables of interest, the objective of this study was to rigorously examine the unique effects of various predictors on the transition to sustainable energy and improvements in environmental quality. Thus, this study adopts the method of moments quantile regression (MMQR), as outlined by Ref. [40]. The MMQR approach was aptly chosen, supported by the outcomes of the Jarque-Bera (JB) test, signifying a non-normal distribution for all variables. This underscores the necessity of employing the MMQR approach to effectively scrutinize the factors influencing energy transition while accommodating the non-normality of the data.

The focus of this research is to scrutinize the influence of environmental governance and economic complexity on energy transition while controlling for variables such as green innovation and economic development. Four distinct models were used in this study. Additionally, we investigated the joint impact of environmental governance and geopolitical risk, as well as economic complexity and geopolitical risk, on energy transition using MMQR estimation analysis. The results of the moment quantile regression method are presented in Table 7 for energy transition, considering four quantiles:25th, 50th, 75th, and 90th, representing the lower, middle, and upper quantiles, respectively.

6.1.1. Environmental governance, and energy transition

Table 7 presents the results regarding the influence of environmental governance (EGOV) on energy transition (ET). The findings indicate that a one percent change in EGOV leads to an 11.38% increase at the 25th quantile (Q0.25), 15.53% increase at the 50th quantile (Q0.50), 17.35% increase at the 75th quantile (Q0.75), and 24.28% increase at the 90th quantile (Q0.90) in energy transition within OECD countries. This demonstrates that environmental governance significantly enhances energy transition across all quantiles. The strict environmental policies implemented by nations make it challenging for activities to pollute the environment. By promoting higher EGOV, the usage of non-renewable energy sources is dejected, encouraging firms and production units to adopt green energy sources [11]. This not only reduces the negative externalities associated with fossil fuels but also maximizes profits through the use of environmentally friendly technology [50]. According to Ref. [99], good governance plays a crucial role in facilitating energy transitions by establishing appropriate policies and coordinating resource allocations. This explains why the influence of environmental governance on clean energy transition may weaken as policymakers' energy governance capacity improves. Therefore, it is crucial to establish proper incentive structures, enhance policy management, and promote the active execution of green policies across all governance echelons to optimize the benefits of green financing frameworks [100]. In summary, the implementation and success of renewable energy transitions depend on a balance between strong environmental governance, which creates a conducive regulatory and policy environment, and a country's economic complexity, which provides the necessary financial, technological, and market capabilities. The contrasting effects of these factors in each country ultimately determine the pace and success of their respective energy transition.

6.1.2. Economic complexity and energy transition

The data outlined in Table 7 model-2 reveal a notable significant positive correlation between economic complexity and the transition to sustainable energy with a positive effect. Specifically, a 1% increase in economic complexity corresponds to various degrees of increase across quartiles within OECD nations. This impact gradient indicates that the effect becomes substantially more pronounced in the higher quartiles. Such outcomes suggest that heightened economic complexity enhances a country's production structure, leading to shifts that are likely to mitigate pollution and foster a transition toward a more technology-driven, energy-efficient economy [22]. The revolution towards technology-intensive growth, facilitated by increased economic complexity, has implications for the energy system, particularly in encouraging the enactment of clean energy sources [6,61]. It is worth noting that the authors [101,102] have studied the linkage between clean sources of energy and financial growth and found similar results. However, with the shift towards cleaner production processes and refined commodities, higher income levels were achieved, leading to a gradual transition from higher-carbon-intensive to lower-carbon-intensive sectors, resulting in reduced CO2 emissions. Therefore, economic complexity is an effective mechanism that Chinese

Table 7

MMQR results for the effect of environmental governance on energy transition.

Quantiles								
Model-1	*Q25*		*Q50*		*Q75*		*Q90*	
Dep.Variable								
	Coeff.	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***
EGOV	1.138**	0.067	1.553**	0.872	1 0.735***	0.009	2.428***	0.000
GPR	−2.926***	0.000	−2.303***	0.000	−2.077***	0.000	−1.389***	0.000
GI	2.704	2.398	2.166**	1.126	1.986**	0.893	1.104**	8.005
GDP	0.975***	0.015	1.502***	0.017	2.446***	0.050	4.397***	0.094
Constant	9.039***	0.017	10.795***	0.061	12.727***	0.206	19.921***	0.363
Quantiles								
Model-2	***Q25***		***Q50***		***Q75***		***Q90***	
Dep.Variable ETI								
	Coeff.	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***
EC	0.601**	0.178	1.355***	0.008	2.654***	0.002	3.239***	0.003
GPR	−3.990***	0.000	−3.379***	0.000	−2.747***	0.000	−1.194***	0.000
GI	4.591**	0.819	3.749*	1.722	3.279**	0.442	3.127***	0.375
GDP	0.871	0.305	1.735***	0.074	3.227***	0.052	5.045***	0.064
Constant	5.165**	0.293	7.126***	0.116	9.865***	0.114	11.609***	0.145

Table 8
MMQR results with the interaction term between EGOV, EC and GPR.

Quantiles								
Model-1	*Q25*		*Q50*		*Q75*		*Q90*	
Dep.Variable ETI								
	Coeff.	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***
EGOV	3.447**	0.783	3.947***	0.913	4.192***	0.622	4.812***	0.293
GPR	−1.101***	0.020	−1.347	0.906	1.495***	0.009	1.006***	0.038
GI	3.260**	1.925	2.989***	0.185	2.360	4.142	2.141***	0.028
GDP	1.304	1.059	1.575**	0.023	1.827***	0.098	2.107***	0.053
EGOVxGPR	−2.822**	0.150	−2.783*	0.135	−2.989**	0.120	−3.028***	0.041
Constant	1.176***	0.081	1.378*	1.042	1.189	1.311	1.201***	0.286
Quantiles								
Model-2	***Q25***		***Q50***		***Q75***		***Q90***	
Dep.Variable ETI								
	Coeff.	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***
EC	0.197***	0.010	0.973**	0.131	2.534***	0.032	4.413***	0.020
GPR	4.883**	3.145	5.123***	0.072	5.842***	0.092	5.919***	0.065
GI	2.546*	1.822	1.954**	0.223	1.666	1.798	1.553***	0.013
GDP	1.011*	0.179	1.716***	0.022	3.134***	0.004	4.840***	0.006
EC ∗ GPR	0.267	1.122	0.386***	0.016	0.415***	0.047	−0.758***	0.024
Constant	3.194	0.193	4.770***	0.044	5.986***	0.019	−7.901***	0.029

policymakers can employ to achieve sustainable development. Furthermore, given global interconnectedness and collaboration in reporting climate change, it is vital for Chinese authorities to leverage the sharing of technological improvements [102].

The effect of the control variables shows that GI has a significant and positive effect on energy transition in both models. Nonetheless, the extent of the impact escalates as we move from the lower to higher quantiles. Similarly, geopolitical risk demonstrates a significant negative influence on clean energy transition in both models from −1.3 to −2.9 and −1.19 to −3.9 from the lower segment to the higher quantile segment. This result was consistent with [103]. Similarly, the results for economic growth show a positive and significant influence on the energy transition in OECD countries. This was confirmed by previous findings [34,73,76]. Fig. 2 provides a visual representation of these effects in the form of quantiles. High quantiles demonstrate a more favorable influence of environmental governance and economic complexity on energy transition than low quantiles. The findings in Table 7 are elaborated on here.

6.2. *Moderating effect of geopolitical risk*

6.2.1. *The moderating effect of geopolitical risk on energy transition*

These results highlight the importance of a cautious approach by relevant departments in the development of energy transition (ET). Blindly pursuing ET without considering the implications of geopolitical risk can hinder the progress of ET and negatively impact energy transition. To comprehensively examine the stimulus of geopolitical risk on various facets, including the nexus between environmental governance and energy transition, economic complexity and energy transition, we introduce interaction terms into our analysis [76,104,105] $EGOV \times GPR$, and $EC \times GPR$, shows combined effect on energy transition in Table 8. The study found some exciting results when we included GPR interaction with EGOV and EC in the model. The evidence reveals that the coefficient of $EGOV \times GPR$ negatively influence the energy transition across all quantiles. The results establish the role of geopolitical risk as a transmission channel through which environmental governance (EGOV) influences energy transition (ET). Our analysis reveals that geopolitical risk exerts a statistically significant negative influence on energy transitions. This finding implies that the escalation of geopolitical risk within the 20 OECD member countries has led to fluctuations in environment-related policies and, consequently, a decrease in energy transition, particularly in higher quantiles. Although this outcome was anticipated, it adds a novel dimension to the existing literature on energy transition. In the early stages of energy transition, the presence of geopolitical risk introduces considerable uncertainty into the optimal combination of environmental policy, which has led pertinent organizational units to reconsider their investment levels in energy technology while also questioning its dependability [75].

The influence of the interaction between geopolitical risk and environmental governance on energy transition is substantial. The results are mixed and positive in the lower quantile and negative influence on energy transition in the higher quantile. This implies that geopolitical risk factors introduce uncertainties and challenges, disrupt energy supply chains, and hinder renewable energy investments. However, effective environmental governance through policies and regulations promotes the adoption of clean energy and encourages sustainable practices. The interplay between these factors can either facilitate or hinder the energy transition process. Stable geopolitics and strong environmental governance support clean energy investments and technological advancements, whereas tension and weak governance can impede progress. Managing geopolitical risks and strengthening environmental governance are crucial for a successful transition to cleaner energy sources, and international cooperation plays a vital role in creating an enabling environment for sustainable energy transition. Evidence suggests that geopolitical risks across countries can be attributed to several factors. Firstly, many countries, including developing economies in the OECD, face challenges in achieving stability in environmental related policy and self-sufficiency in renewable energy production and technology. Dependency on imported energy and renewable technologies may exacerbate geopolitical strain and impede local cooperative efforts towards renewable energy creation. Confronted with escalating geopolitical complexities, nations frequently opt for readily accessible energy options, such as fossil fuels, rather than investing in renewable energy advancements [106]. This focus on immediate energy needs can lead to a lack of emphasis on developing streamlined renewable energy consumption, thereby hindering progress in the adoption of renewable energy sources [75,100].

The consequences of the combined influence of economic complexity and geopolitical risk on energy transition are shown in Table 10. The positive effect of $EC \times GPR$, on ET in lower quantile. This effect becomes negative and significant at higher quantiles. This implies that the intersection of geopolitical risk and economic complexity has a substantial influence on clean energy transition. Economically complex countries are better equipped to navigate geopolitical risks and diversify their energy sources through renewable energy investments. However, geopolitical risks still pose challenges by disrupting global supply chains

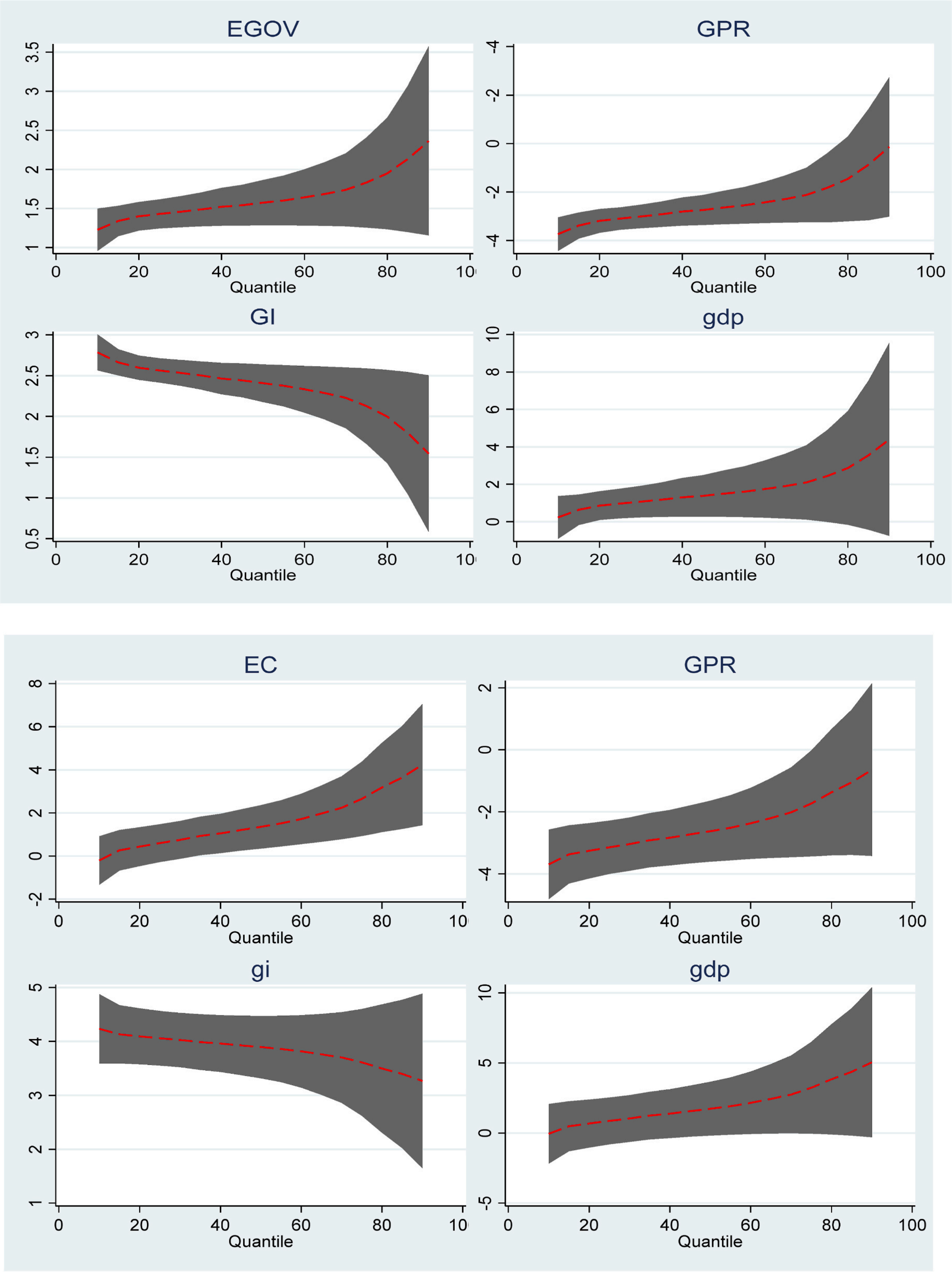

Fig. 2. MMQR ghraph.

and trade. Effective management of geopolitical risks and leveraging economic complexity are crucial for resilient and sustainable energy transitions. International cooperation, collaboration, and knowledge sharing play vital roles in addressing geopolitical risks and enhancing economic complexity, facilitating a smooth transition to cleaner energy sources globally [101,107,108]. Regardless of a nation's economic expansion, economic complexity does not significantly influence the adoption of clean energy in countries with minimal renewable energy utilization. However, as nations evolve toward more advanced stages of clean energy consumption, economic complexity tends to exert a negative impact on the further uptake of renewable energy. In other words, economic complexity becomes less influential and may hinder

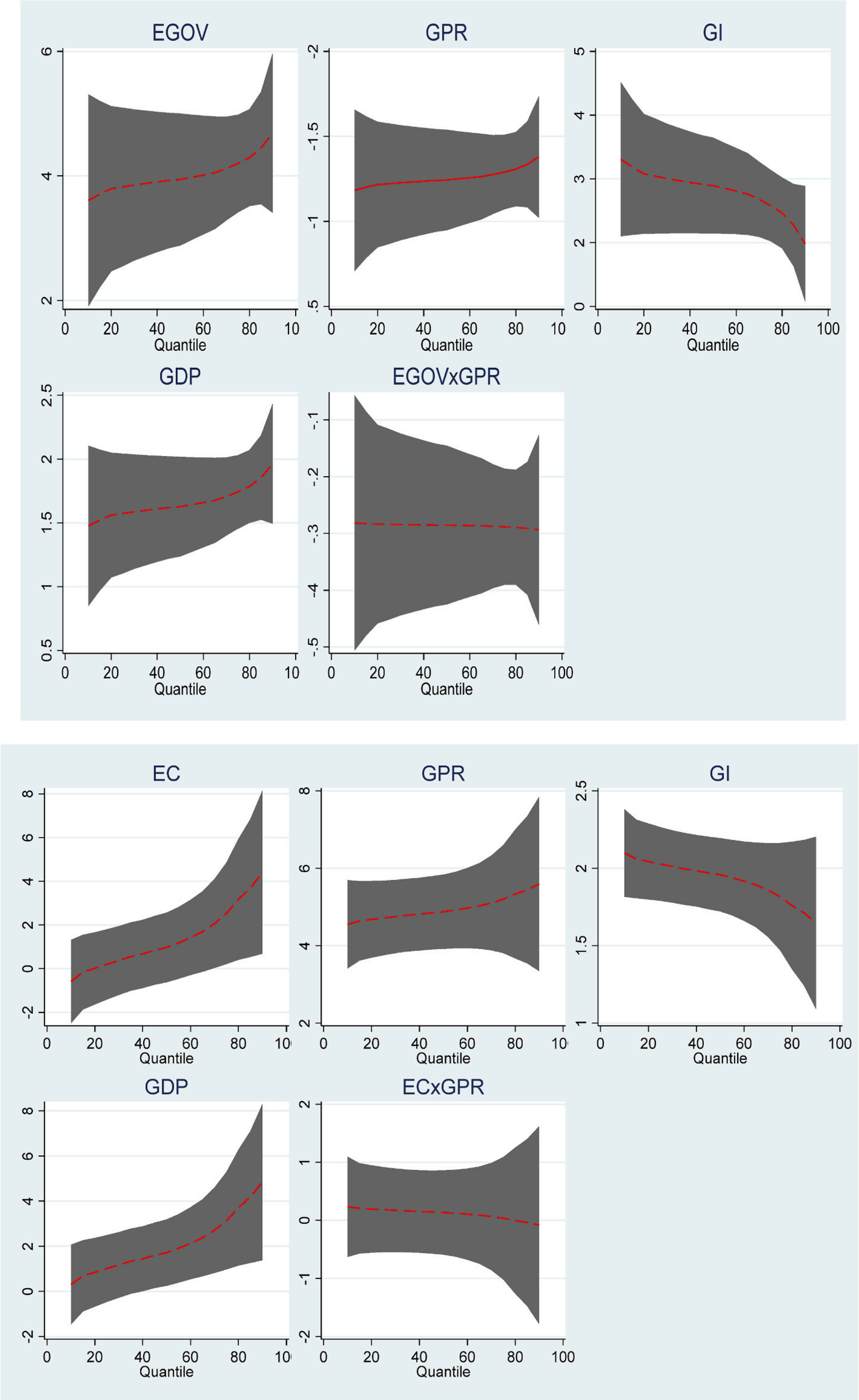

Fig. 3. MMQR ghraph.

the acceleration of renewable energy adoption in more advanced stages of transition [76,109].

6.3. Robustness check - BSQR

We assessed the robustness of the model using Bootstrap Quantile Regressions (BSQR), as displayed in Table 9. Statistical tests confirmed the consistency and efficiency of the proposed model. Notably, the tables present significant findings, with a particular emphasis on quantiles Q (0.75) and Q (0.90). However, it is significant to note that although the coefficient signs indicate positive results, they are also statistically significant. Visual representations of the coefficients for all variables across different quantiles, Fig. 4 in this section displays the graphical presentation. This illustration provides a comprehensive view of the relationships between the variables, energy transition, and environmental quality outcomes across various quantiles. The robustness results of the (BSQR) model estimates are shown in Fig. 4.

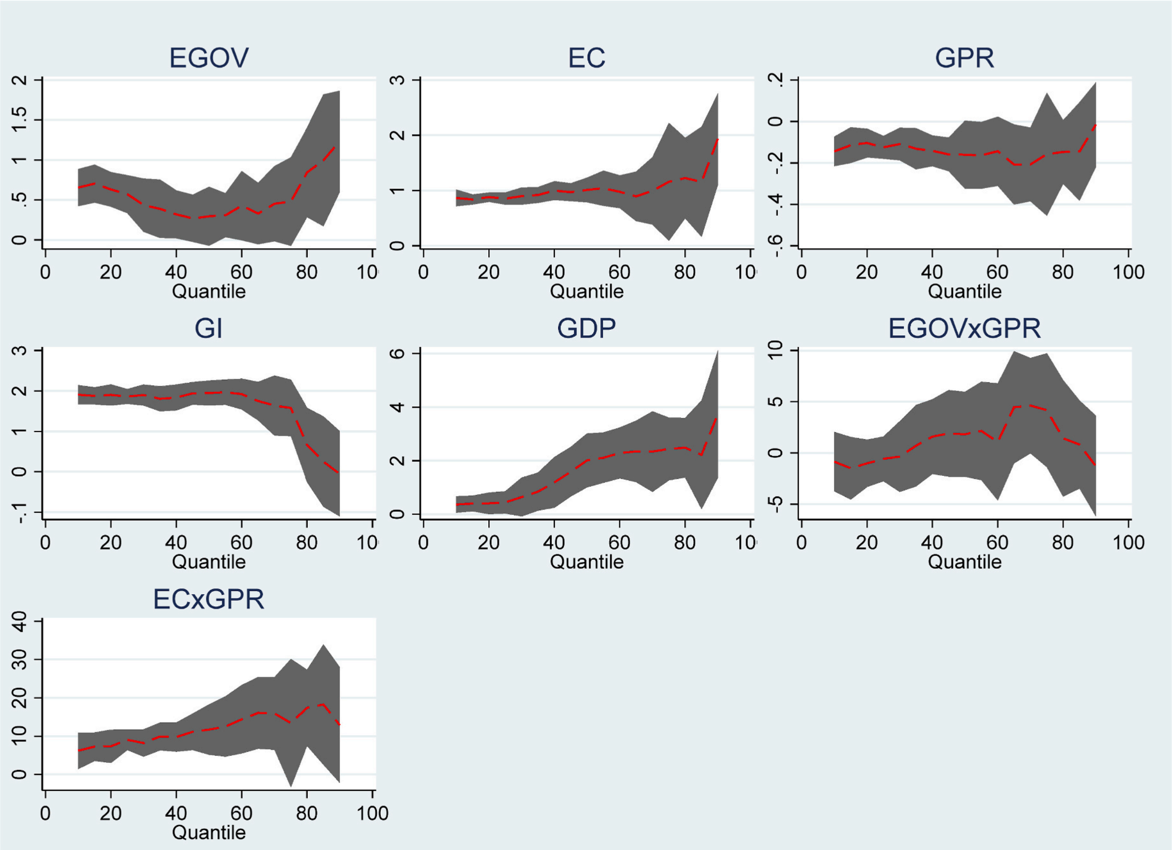

Fig. 4. Graphical depiction of the BSQR coefficients.

Table 9
Robustness results – BSQR.

Model: 1: Energy transition

Variables	$Q_{0.25}$		$Q_{0.50}$		$Q_{0.75}$		$Q_{0.90}$	
	Coeff.	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***	***Coeff.***	***Prob.***
EGOV	0.572***	0.048	0.321**	0.156	0.350***	0.004	1.332**	0.918
EC	0.934	1.061	1.002***	0.039	0.901**	0.138	1.869***	0.049
GPR	−2.186*	−0.110	−2.061**	−0.119	−2.101	0.166	−2.647	2.18
GI	2.093***	1.400	2.017***	0.487	1.211***	0.135	0.063	1.003
GDP	0.414	2.451	2.011***	0.000	2.438	3.910	3.743**	2.12
EGOVxGPR	−0.573*	−0.311	1.825**	0.417	4.174***	1.304	−1.277**	−0.032
ECxGPR	9.041**	4.250	11.701***	0.000	13.414***	2.111	−12.897	1.39
Constant	3.575***	1.793	−2.172***	0.000	3.908**	1.523	−10.364	−1.181

Table 10
Dumitrescu-Hurlin panel causality test.

	W-Stat.	Zbar-Stat.	Prob.
EGOV → ET	5.65775***	6.56856	0.000
EC → ET	5.35411***	5.99606	0.000
GI → ET	2.28725***	0.21369	0.000
GPR → ET	5.19300***	5.63720	0.000
GDP → ET	5.13186***	5.52276	0.000
EGOVXGPR → ET	6.73926***	1.06593	0.001
ECXGPR → ET	4.51198***	−1.24804	0.000

6.4. Causality analysis

This study extends the analysis conducted using the MMQR approach by examining the causal nexus among the variables to verify the robustness of the findings. The researchers employed the causality analysis method, which provides further insight into the relationships among the variables. The outcomes of this analysis, presented in Table 10, show the causal associations between environmental governance, economic complexity, green innovation, geopolitical risk, economic growth, energy transition, and carbon emissions. The outcomes of the Dumitrescu and Hurlin (2012) Granger causality analysis demonstrate noteworthy links among these factors and both energy transition and carbon emissions. Specifically, the analysis revealed that interventions targeting these areas have the potential to significantly support energy transitions and improve environmental quality. By focusing on environmental governance, economic complexity, green innovation, geopolitical risk, and economic growth, policymakers and stakeholders can effectively decrease CO2 emissions and enhance environmental conditions. The adoption of such strategies holds great promise for OECD economies in their pursuit of sustainable development objectives. An integrated approach encompassing the factors mentioned above can pave the way for greener and more sustainable development. By utilizing the insights gained from this analysis of causality, decision-makers can develop and implement effective policies to tackle carbon emissions and promote environmental well-being. This research underscores the importance of adopting a multifaceted approach to addressing climate change and achieving development goals within OECD economies. Fig. 5 shown graphical representation of empirical outcomes of the study.

Furthermore, if environmental governance exerts a causal influence on energy transitions, it can be inferred that improvements in environmental governance precede and predict advancements in energy transitions. In other words, stronger environmental governance serves as a leading indicator of progress in energy transition. Conversely, if environmental governance Granger-causes carbon emissions, this implies that more robust environmental governance measures lead to decreased carbon emissions. By implementing stricter regulations and policies, industries and individuals can be encouraged to adopt cleaner energy sources and practices. If geopolitical risk Granger-causes energy transition, it suggests that changes in geopolitical risk factors precede and predict shifts in energy transition. High geopolitical risk may motivate countries to seek more stable and sustainable energy sources. In the case of carbon emissions, if geopolitical risk Granger-causes emissions, it implies that increased geopolitical instability leads to higher emissions. This could occur if conflicts disrupt energy supplies or if countries resort to less environmentally friendly energy sources during geopolitical crises. The magnitude of the causal relationship between geopolitical risk and energy transition or emissions can be modulated by the frequency and intensity of geopolitical events. Significant conflicts or disruptions may have a substantial impact. Additionally, the response to geopolitical risk can vary across countries. Some nations may be more resilient or adaptable to geopolitical challenges, thus mitigating the magnitude of the causal relationship.

7. Discussion and economic intuition

The preceding discussion provides an overview of econometric analyses and their estimated outcomes. The findings indicate a significant relationship between environmental governance (EGOV), economic complexity (EC), and energy transition in OECD economies. Additionally, a regression analysis revealed that geopolitical risk (GPR) plays a crucial role in facilitating clean energy transition.

This study introduces an intriguing element by including the interaction of GPR with these variables (EGOV × GPR and EC × GPR) in the models. The results demonstrate that the EGOV × GPR interaction negatively influences the energy transition in lower-to-higher quantiles. These results are consistent with the conclusions of previous studies [1,11,34,76,100,101]. These findings provide valuable insights into the complex association among environmental governance, economic complexity, geopolitical risk, and energy transition in OECD economies. By considering the interactions between these variables, policymakers and stakeholders can gain a deeper understanding of how different factors interact and influence the outcomes of energy transition initiatives. The direct effects of economic complexity on energy transition (ET) indicate that economic complexity significantly and positively influences the transition to sustainable energy. The extent of this impact shows notable variation when moving from lower to higher quantiles. This emphasizes the necessity of structural shifts toward more complex products as a means of reducing emissions. These results are consistent with those of previous studies [52,90,110]. The interaction between economic complexity (EC) and geopolitical risk (GPR) affects energy transition. The results show that the EC × GPR coefficient positively influences energy transition in the lower quantiles. However, this effect becomes negative and reaches statistical significance in higher quantiles. Importantly, the combined influence of the variables, as

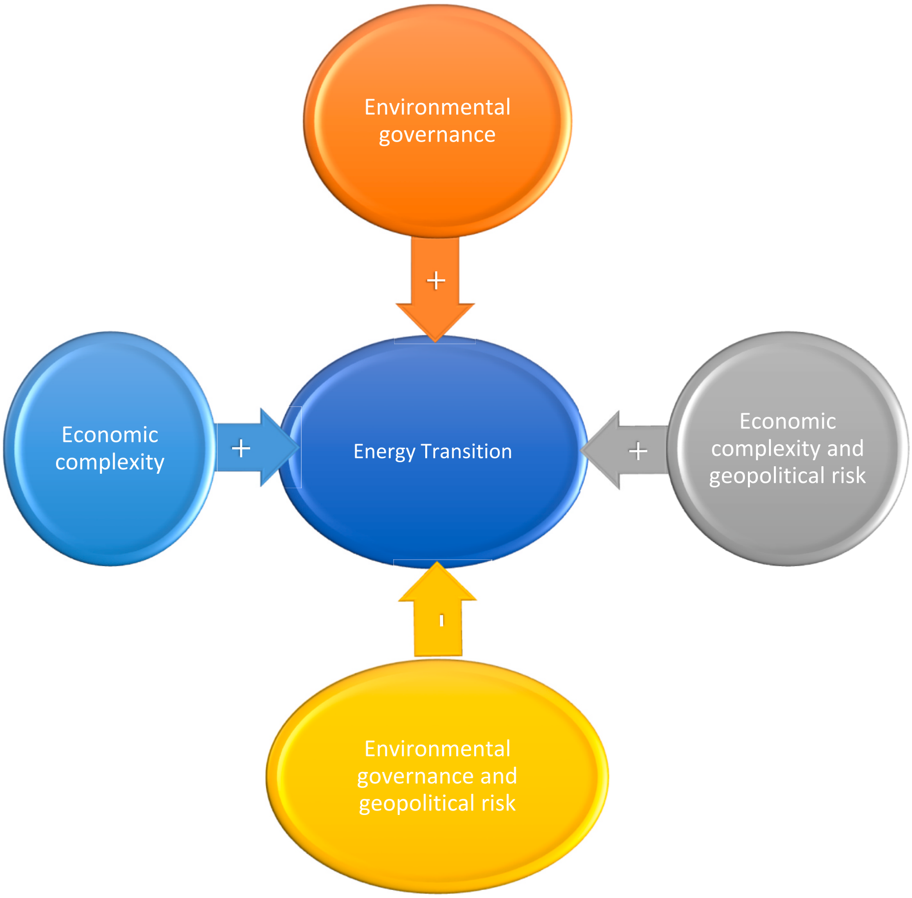

Fig:5. Graphical presentation of estimated results.

experiential through the interaction terms, was found to be relatively more complex than the direct impact. This confirms the significance of geopolitical risk in accelerating the energy transition.

As an economy evolves in its structural dimensions, marked by increased economic complexity, there is a corresponding surge in energy needs to sustain the growing scope of production activities. However, this also impacts the adoption of renewable energy sources, which might have been a favorable choice, remains constrained in several countries, and is influenced by a multitude of factors. These aspects include adverse weather conditions, inadequate technical expertise in harnessing and managing renewable energy, substantial capital requirements for installation and maintenance, and the high cost of energy storage. As a result, economic agents tend to rely on fossil fuels, which are more cost-efficient and commercially viable, given the existing limitations of renewable energy sources. This situation is prevalent in many countries worldwide, where the infrastructure for energy consumption predominantly relies on nonrenewable sources. Consequently, as economies become more diversified, the energy required for the production of goods, products, and innovation increases. Nevertheless, the current energy infrastructure is primarily based on non-renewable sources, such as fossil fuels. This reliance on non-renewable energy for production processes is particularly evident in nations such as China, the world's leading consumer of coal. This situation leaves limited space for the integration of renewable energy sources. Therefore, there is a pressing need to explore how the complexity of economies can support and facilitate the transition from nonrenewable to clean energy sources. It is necessary to address the challenges posed by economic complexity, which reduces clean energy consumption across different economic groups. This requires concerted efforts and initiatives to develop renewable energy infrastructure, enhance technological capabilities, and overcome barriers that hinder the widespread adoption of clean energy solutions. By doing so, economies can effectively shift towards sustainable and renewable energy systems, mitigating the environmental impacts associated with non-renewable energy sources.

Our findings align with the views expressed by Ref. [111], particularly in light of the recent COP26 agreement that aims to phase out unabated coal usage in order to limit global warming to 1.5 °C [111]. indicated that the shift from coal-based energy to renewable sources may face considerable challenges. These complexities may arise from a variety of elements, such as technical obstacles, market limitations, regional disparities, and policy incongruities. The results of our study align with those of previous studies [59,112]; however, they differ from the results reported by Ref. [113], who examined seven emerging and developed economies. We are certain that the discrepancies between our results and these can be attributed to the limited number of countries considered in their study and their reliance on linear models. It is important to note that environmental and economic variables often exhibit nonlinear relationships, which might not be adequately captured by linear models, a broader range of countries, or employing more sophisticated modelling techniques that account for nonlinearity. Our study provides a more comprehensive understanding of the complexities involved in the transition from nonrenewable to clean energy. These insights can contribute to more effective policymaking and strategies for achieving sustainable energy transitions on a global scale.

Strong environmental governance can potentially encourage the development of economic complexity in environmentally friendly sectors, such as renewable energy technologies or sustainable manufacturing. Stringent regulations can promote innovation and investment in clean industries. Economic complexity can influence environmental governance, as wealthier and more economically diverse countries may have greater resources to allocate to environmental protection and sustainability initiatives, resulting in more robust governance frameworks. Geopolitical risk factors can also impact environmental governance. For example, in regions with political instability or conflict, the ability to enforce and implement environmental regulations may be compromised. Geopolitical tensions can also hinder cross-border cooperation on environmental issues. Environmental governance can help mitigate certain geopolitical risks. By promoting environmental sustainability, countries may reduce their dependence on geopolitically volatile energy sources (e.g., fossil fuels) and enhance energy security. Economic complexity can also mitigate geopolitical risks related to energy supply. Diversified economies with multiple industries and trading partners may be less vulnerable to disruptions in energy imports or exports. However, geopolitical risks can influence economic complexity by disrupting trade relationships, supply chains, and investment flows. Geopolitical tensions can also deter foreign investment or hinder economic diversification.

The impact of these variables on energy transition is not straightforward and may vary across countries and regions. A country with strong environmental governance, high economic complexity, and low geopolitical risk may have favorable conditions for a successful energy transition. However, the presence of one factor (e.g., strong environmental governance) may offset the limitations imposed by another (e.g., high geopolitical risk). Robust governance can help overcome geopolitical challenges in achieving energy transition goals.

8. Conclusions and policy implications

In this study, we investigated the impact of several determinant variables on energy transition in 20 OECD countries between 1990 and 2021. Our analysis emphasized the role of environmental governance and economic complexity in driving these outcomes. Additionally, we assessed the combined effects of geopolitical risk, environmental governance, and economic complexity on energy transition in OECD economies. We employed second-generation techniques, such as stationarity and co-integration approaches. Methodologically, we also utilize a novel technique called the moment quantile regression (MMQR) approach, which offers unique advantages in establishing relationships across the conditional distribution of dependent variables. Using this approach, we identified the heterogeneous impact of our independent variables on energy transitions. Our empirical analysis provides compelling evidence that environmental governance plays a crucial role in facilitating energy transitions and reducing carbon emissions. Furthermore, our results indicate that economic complexity has a significantly positive effect on energy transitions; however, it also contributes to carbon emissions, particularly in the lower quantiles. This suggests that as countries experienced increased economic complexity and higher energy demands, scale effects came into play, resulting in elevated CO2 emissions within OECD economies.

Various tests were conducted to confirm the validity of our findings. We employed Bootstrap Quantile Regression (BSQR) estimators to assess the effectiveness of the MMQR approach. Furthermore, we explored the causal link between the factors influencing energy transition and carbon emissions using Dumitrescu-Hurlin panel causality tests. Our investigation revealed that both environmental governance and geopolitical risk, as well as economic complexity and geopolitical risk, play crucial roles in driving energy transitions and carbon emissions. In our analysis, we considered several control variables and discovered that elements such as green innovation and economic growth have a significant impact on the increase in energy transition.

8.1. Policy implications

This study proposes policies that could help OECD economies transition towards clean energy and achieve environmental stability. Our findings have several policy implications. First, OECD economies must adopt inclusive and long-term policies to maximize the benefits of energy transition and environmental regulations. These include promoting the transition to clean energy, implementing effective environmental regulations, and establishing strong governance mechanisms. International cooperation is crucial for countries to collaborate, share best practices, and coordinate their policies. Green finance mechanisms should be developed, and COP27 participants must fulfil their commitments to green source investment and clean energy. IEA members should enhance collaboration in energy transition and environmental regulations while creating a strategic committee to assess policy implementation and long-term impacts. Consistent long-term policies are essential for environmental stability, necessitating an integrated plan for energy transition and environmental regulation. Second, environmental governance should restructure policies to provide incentives for the use of cleaner energy sources and accelerate the transition to renewable energy. Implementing taxes on polluting activities can reduce pollution and improve the environment in the long term. OECD economies invest more in green energy. The promotion of renewable energy is a critical objective for governments worldwide, and it is essential to consider the economic challenges in the process. To encourage this transition while addressing economic complexities, governments can take the following practical steps: establish clear and ambitious renewable energy targets and specify the percentage of energy to be generated from renewable sources by a certain date. These targets provide a roadmap for transition. Enact and enforce policies that provide incentives for renewable energy adoption such as feed-in tariffs, tax credits, grants, and subsidies. These policies can help offset the initial cost of renewable energy projects, making them financially attractive. Collaborate with the private sector to develop renewable energy projects. Public-private partnerships can leverage private sector expertise, innovation, and financing to accelerate the deployment of renewable energy technologies. Allocate resources to research and development (R&D) initiatives focused on renewable energy technologies. Governments can fund R&D projects, support innovation hubs, and promote technology transfer to advance the state of renewable energy. Invest the development of renewable energy infrastructure, including solar and wind farms, hydroelectric facilities, and energy storage systems. Ensure that the infrastructure is resilient. Establish mechanisms to facilitate access to financing for renewable energy projects. This can include creating green investment funds, offering low-interest loans, and encouraging private sector investments through green bonds. Encourage diversification of renewable energy sources to reduce risk and ensure energy security. Supports various technologies, including solar, wind, hydro, geothermal, and biomass technologies. Recognize and address economic complexities, such as economic dependence on fossil fuels or the need for a just transition for affected workers and communities. By taking these steps, governments can ensure a smooth transition to renewable energy to address the economic complexities.

First, Countries with lower economic complexity have seen an upsurge in the relative share of energy transition, while overall renewable energy production has remained stable. This shift has had a positive environmental impact, as it reduces air pollution without the scale effects associated with energy. In contrast, countries with higher economic complexity experience two major changes: an increase in the total amount of clean energy produced and a higher share of solar and wind energy. Although the clean energy production process causes pollution, the intensity of emissions decreases with the utilization of new energy sources. Therefore, a country with higher economic complexity should emphasize clean energy production, optimize processes, and create structural fluctuations in the industry to reduce CO2 emissions. In contrast, countries with low economic complexity should focus on energy supply and demand management, develop industrial strategies, and promote innovations to transition to renewable energy and reduce CO2 emissions. Implementing environmental policies, such as carbon taxes, investments in clean technologies, grants, and incentives for renewable energy infrastructure, will also contribute to the growth of renewable energy. Policymakers can focus on three key aspects to facilitate energy transition in OECD countries: encouraging environmental progress, aligning financial growth, and examining globalization. These policy instruments should be combined with climate policies to advance the objectives of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Countries with less developed economies can maximize their potential for energy transition and increase renewable energy production by adopting a strategic and targeted approach. First, evaluate the country's strengths and resources, such as solar, wind, geothermal, and biomass energy potential. Set specific and attainable renewable energy production goals that align with international agreements and consider local energy requirements. Allocate resources for infrastructure, R&D, and collaborations to boost the efficiency and affordability of renewable technologies. Offers incentives and stable policies to attract investments in renewable energy projects. Collaborate with other countries to transfer technology and knowledge. Encouraging diversification of renewable energy sources and long-term energy transition plans. By following these steps and customizing strategies according to their specific circumstances, developing countries can make significant contributions to the global energy transition, while promoting sustainable and affordable energy solutions for their populations.

Second, policymakers must recognize that economic complexity can hinder energy system efficiency and impede renewable energy transitions. Development based solely on economic complexity may undermine efforts to achieve environmental sustainability and mitigate climate change. It is crucial for policymakers to address the factors that lead firms to favor conventional energy over renewables, especially in the face of growing energy demand driven by economic complexity. Governments can provide subsidies and grants to promote the deployment of renewable energy and reduce initial capital costs. Energy efficiency standards, conducting campaigns, and adjusting the existing infrastructure to support renewable energy are important policy initiatives. It is suggested that emerging economies incorporate privatization as a complement to their policies, with the aim of promoting the production of clean electricity. Investment in renewable energy infrastructure and research on innovative technologies can increase electricity generation capacity and stabilize water levels. Stable policies that promote renewable energy expansion should be implemented to overcome government uncertainties. International cooperation, technology transfer, and financial provision can aid in the transition to clean energy and address global climate change challenges. Future studies should explore the broader influence of economic complexity on various economic outcomes by considering nonlinearities and regime changes.

Third, Policymakers ought to consider these interactions when devising strategies for sustainable energy transition. Policymakers can adopt complementary approaches by strengthening environmental governance, promoting economic complexity in green sectors, and addressing geopolitical risks through diplomacy and international cooperation. Effective policies must foster synergy among these variables and address any potential conflicts or trade-offs that may arise. The adoption of sustainable energy policies is a complex process that requires careful planning and stakeholder involvement. To ensure successful implementation, governments, industry representatives, environmental organizations, local communities, and research institutions must work together. Therefore, a comprehensive policy framework that includes clear objectives, targets, and timelines must be developed. Public consultations should be held, and stakeholders should be involved in the decision-making process to build consensus. Legislation that supports renewable energy development and provides policy continuity should be enacted. Long-term renewable energy targets that extend beyond political cycles should be established. Financial incentives such as feed-in tariffs, tax credits, grants, and subsidies can also be offered. Germany, Denmark, and Sweden have successfully adopted inclusive and long-term renewable energy policies. German Energiewende is an example of long-term policy planning that includes ambitious targets for renewable energy adoption and energy efficiency. Denmark has pursued a long-term vision for renewable energy with a strong focus on wind power. Sweden has implemented a holistic approach to energy policy that combines renewable energy targets with energy-efficiency measures. These countries have demonstrated that a combination of clear long-term goals, stakeholder engagement, financial incentives, and legislative support can lead to successful and sustainable renewable energy transitions.

Finally, in the Russia-Ukraine War era, promoting clean energy demand, the international community, including OECD economies, should prioritize geopolitical stability and cooperation. Geopolitical tensions can hinder the exchange of clean energy transitions and technological collaborations, jeopardizing efforts to address climate change. Additionally, OECD economies should control pollution and CO2 emissions to achieve environmental cleanliness and promote green technologies. Policymakers should also leverage economic growth and globalization to drive renewable energy demand, facilitating a swift transition from fossil fuels to renewables. The ongoing Russia-Ukraine War highlights the need for OECD economies to ensure geopolitical stability and cooperation in the energy transition sector. To achieve this, it is crucial to accelerate the adoption of renewable energy sources, such as solar, wind, hydro, and geothermal, and invest in the research and development of alternative technologies, including hydrogen fuel and advanced nuclear reactors. Upgrading the energy infrastructure and enhancing the resilience of energy networks against cyber and physical threats are also essential. Other important measures include promoting energy efficiency, building strategic reserves of essential energy resources, and coordinating the release of these reserves among OECD countries during crises. Diplomatic efforts to resolve conflicts impacting energy supply chains, strengthening international institutions by overseeing energy trade and cooperation, and fostering partnerships for shared energy projects and development are also necessary. Implementing regulatory frameworks that encourage investment in renewable energy, penalize unsustainable practices, and create international agreements to secure energy routes and infrastructure are also essential. Collaboration between governments and the private sector to finance and develop new energy technologies is important.

In short, non-OECD countries frequently employ inventive governance practices that can provide valuable insights for OECD countries, especially in the realm of energy transition. Establishing effective policies that promote the utilization of renewable and low-carbon energy sources while reducing the use of fossil fuels is crucial for a sustainable energy transition. To achieve this, the following tactics should be implemented: prioritizing renewable energy sources such as solar, wind, and hydropower for electricity generation; implementing clean coal technologies and carbon capture and sequestration in countries with substantial coal reserves; exploring nuclear power as a low-GHG emission option while considering geopolitical stability; developing cutting-edge batteries, high-efficiency conversion technologies, and resilient grids to support renewable energy sources; electrifying transport with electricity from green sources; enhancing energy efficiency and integrating Carbon Capture and Storage (CCS) in power plants; and addressing challenges such as public acceptance, behavioral changes, and cost limitations.

8.2. Limitations of study and future directions

In this part of the article, we provide a summary of the potential constraints of this research and suggest suggestions for future studies to address these limitations. The policy framework developed in this study considers environmental governance, economic complexity, and geopolitical risks in regional and national environmental policies. Second, future research may benefit from conducting more in-depth evaluations of geopolitical risk. Rather than relying solely on a global-scale geopolitical risk index, it could be valuable to analyze geopolitical risk at the country level or by utilizing specific sub-indices. These sub-indices might include the geopolitical threats (GPRT) index and the geopolitical acts (GPRA) index, which would enable a more fine-grained understanding of the various dimensions of geopolitical risk within and between countries. By adopting this approach, researchers can gain a more comprehensive and detailed perspective on the geopolitical landscape, allowing them to explore the complex nature of geopolitical risk and its consequences for energy transitions, among other aspects. However, the study acknowledges limitations, such as the exclusion of cross-border measurements of environmental goods and green financing within OECD member countries. Nevertheless, the framework can be generalized and applied to other developed and emerging economies that require the realignment of their environmental policies. It serves as a benchmark for countries that aim to achieve Sustainable Development Goals (SDGs). Additionally, future studies should expand the dataset beyond the panel of 20 OECD countries from 1990 to 2021 and include the impact of the COVID-19 pandemic, among other factors. Therefore, it is important to acknowledge the limitations of previous research that did not consider cross-border measurements of environmental goods and the effects of the COVID-19 pandemic. Future studies could address these limitations by developing methodologies to track and analyze cross-border environmental goods and services. Additionally, analyzing changes in consumer behavior and industrial activity during and after the pandemic, as well as investigating the effects of reduced transportation and industrial activity on air and water quality, can provide a more comprehensive understanding. Including economic variables such as GDP, trade balances, and investment in green technologies can also provide valuable insights. Moreover, assessing public awareness, attitudes towards environmental conservation, and changes in lifestyle post-pandemic can offer a more holistic perspective. Exploring the role of new technologies in environmental monitoring and conservation can provide valuable information. Finally, studying the impact of new environmental policies and regulations introduced during and after the COVID-19 pandemic can help inform future environmental conservation efforts.

CRediT authorship contribution statement

Satar Bakhsh: Conceptualization, Methodology, Validation, Writing – review & editing. **Wei Zhang:** Writing – review & editing, Supervision. **Kishwar Ali:** Writing – review & editing, Writing – original draft. **Judit Oláh:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

- None of the authors of this paper has any financial or personal relationship with any other person or organization that could inappropriately influence or affect the content of the paper.
- Explicitly declare that there are “no competing interests at play and no conflict of interest” with any other person or organizations that could unduly influence or distort the content of the paper.

Data availability

Data will be made available on request.

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