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Country-level Risk and Green Energy Transition: Evaluating Political Risk and Human Capital in OECD Economies

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Abstract

In today's rapidly evolving world, the transition towards green energy remains momentous in attaining ecological sustainability. In this respect, the present study intends to elucidate factors influencing the green energy transition in OECD economies from 2004 to 2020. We use several diagnostic measures to validate the heterogeneity of slopes and cross-sectional dependence in the panel. Nevertheless, cointegration exists between the study variables, such as green energy, political risk, economic risk, financial risk, human capital, eco-innovation and energy efficiency. Using fixed effect and random effect approaches, we conclude that political risk, human capital and energy efficiency are significant and leading drivers of green energy transition in the region. However, economic expansion, financial risk and economic risk are significant barriers to transitioning towards green energy in the selected economies. The outcomes are robust, as authenticated by linear regression with a heteroskedastic panel-corrected standard error approach. We recommend the minimization of political, financial and economic risk, while improvements in environment-related R&D investment could further boost the transition process towards green energy.

Keywords: Green energy transition, political risk, human capital, financial risk, economic risk, eco-innovation, energy efficiency, economic growth

JEL Classification: F43, O13, Q43

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1. Introduction

1.1 Background

The shift to green energy sources signals a paradigmatic transformation of global energy systems. Emergent from the confluence of environmental sustainability, energy security and economic resilience, this transition has deep implications for how societies are powered. In this context, the interplay of countries' risks, including political risk, financial risk and economic risk, becomes central to understanding the contours of the green energy transition. Political risk encompasses a combination of factors, including policy instability, regulatory uncertainty and geopolitical tensions, which may influence government decisions, market dynamics and investment climates for renewable energy (Bataineh *et al*., 2023; Becker, 2023). However, economic risk reflects the extent of broader macroeconomic uncertainties, such as inflation rates, currency variations and economic volatility, which might affect the financial viability and ease of investments in green energy (Stern, 2007). On the other hand, financial risk alludes to concerns in financial markets, investment climates and funding accessibility, which follow the fulfilment and profitability of green energy projects (Linnerooth-Bayer and Hochrainer-Stigler, 2015). This study provides an inclusive portrait of the nexus of countries' risk factors and green energy transition.

1.2 Risk components and green energy

Going ahead with the green energy transition in the face of political risk is a complex task. Government policies and regulatory frameworks are central to creating the investment landscape within which the renewable energy sector operates and the market dynamics that it confronts. Policy instability and regulatory uncertainty can deter investors and erode confidence in renewable energy projects, leading to delays, cancellations or suboptimal outcomes (Becker, 2023). In contrast, policy environments conducive to investment, backed by clear regulatory frameworks, are necessary if renewable energy technologies are to be adopted by industry, attract investment and stimulate innovation (O'Brien *et al*., 2010). Concern for the critical role that political stability and policy coherence play in accelerating the green energy transition is evident in research that directs governments towards long-term visibility and commitment to renewable energy goals (Sovacool, 2016).

Additionally, economic risk is another significant determinant of the green energy transition. Macroeconomic uncertainties can influence investment decisions, market conditions and allocation of resources to renewable energy. For instance, fluctuations in economic indicators such as the GDP growth rate, inflation rate and exchange rate can directly affect the financial outlook and profitability of clean energy projects and, consequently, the attractiveness of these projects to investors (Stern, 2007). In addition, the flow of capital to investments in green energy may be constrained as a consequence of minimal funding availability, increased investor aversion to risk and tighter credit conditions, which can be caused by economic downturns or recessions (Linnerooth-Bayer and Hochrainer-Stigler, 2015). Economic risk also presents an opportunity for a green energy transition. Governments and investors alike seek to restrain vulnerability to fossil fuel price spikes (Stern, 2007) and diversify the sources of energy, and growing the renewable sector has the potential to stimulate economic growth.

The green energy transition is marked by a number of financial risks. For example, uncertainties and volatilities on financial markets, investment climates and available funding can limit the expansion, deployment and scaling of green energy projects. Fluctuations in exchange rates, interest rates and commodity prices can affect project costs, revenues and profitability, which can in turn affect the financial feasibility and perceived attractiveness of green energy investments (Linnerooth-Bayer and Hochrainer-Stigler, 2015). Similarly, concerns related to project financing, creditworthiness and revenue certainty can deter investors and lenders from contributing capital to fund renewable energy projects, particularly in new markets or in sectors with higher perceived risks (O'Brien *et al*., 2010). Nonetheless, several pioneering financial instruments, including renewable energy funds, green bonds and carbon markets, are emerging to help mitigate these financial risks and spur capital towards a green energy transition. Nevertheless, the evaluation of overall risk factors, such as political risk, financial risk and economic risk, can strengthen persistent knowledge and help policymakers rethink feasible alterations in policies.

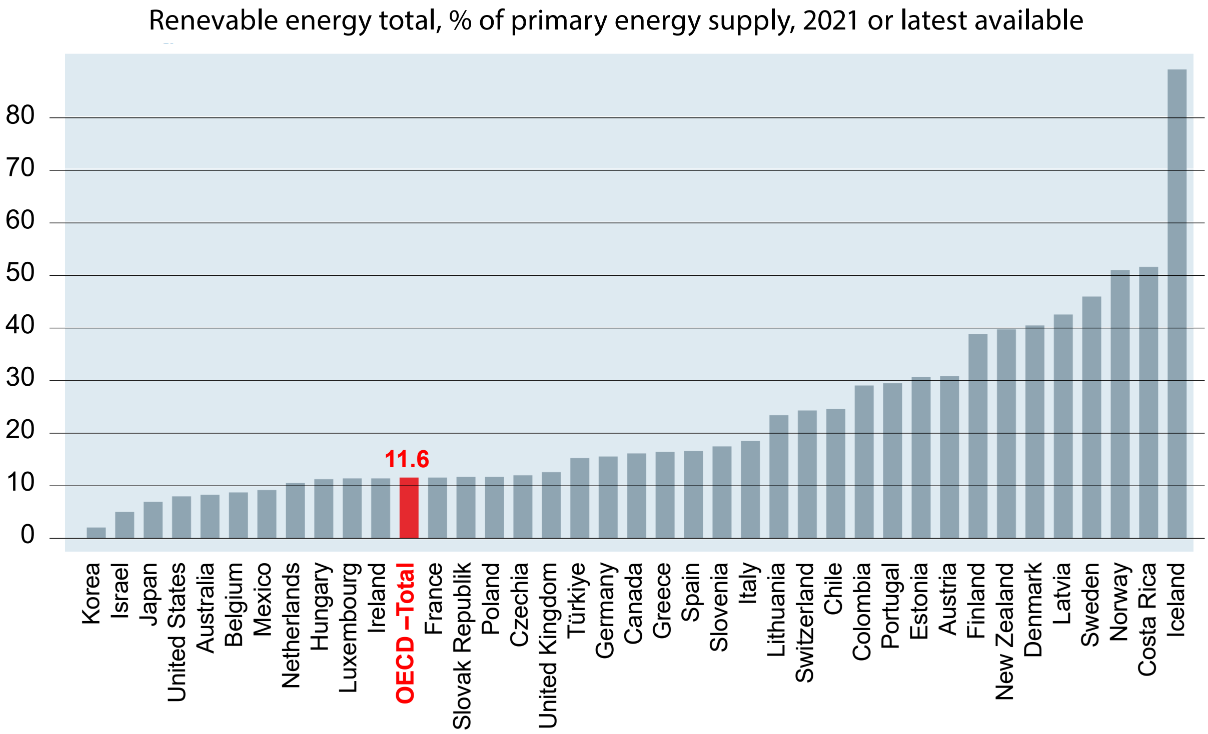
In the context of sustainability, the associations among human capital, economic expansion, environmental technologies and energy efficiency are crucial to determining the course of a green energy transition. Human capital such as qualified labour, research capability and technological knowledge is crucial to the green energy transition process. It facilitates innovation, technology diffusion and overcoming the various barriers to renewable energy deployment (Chapman and Itaoka, 2018). Investments in education, training and research and development are essential for developing a skilled workforce capable of developing green energy solutions and supporting sustainable development goals (Pollitt, 2012). On the other hand, economic expansion affects the dynamics of the green energy transition by influencing energy demand, patterns of investment and policy priorities within economies. Rapid economic growth might drive energy consumption and carbon emissions, but it also creates opportunities for investment in renewable energy technologies, the development of new infrastructure and the support of innovation for sustainability. Understanding the associations among human capital, economic progress and the green energy transition is crucial to designing policies and strategies that can lead to sustainable development pathways.

Moreover, environmental technologies are critical to the green energy transition. They offer efficient, clean, renewable substitutes for conventional energy sources. For instance, wind turbines, solar panels, smart grid technologies and energy-efficient appliances can lead to conversion towards a low-emission economy and help alleviate climate change. Investments in the research, development and deployment of environmental technologies are essential for accelerating the green energy transition and meeting sustainable energy goals (Jo *et al*., 2015; Wen *et al*., 2021). Similarly, energy efficiency measures are critical to the green energy transition because they help optimize energy use, reduce energy consumption and lower environmental impacts across the entire economy. The introduction of energy efficiency schemes to transport, buildings, manufacturing and other sectors in a country allows them to lower their carbon footprint, increase energy security and support sustainable development. Energy efficiency supports the green energy transition by reducing overall energy demand, lowering costs and increasing the competitiveness of renewable energy technologies (IEA, 2021). Despite the role of both these factors in determining environmental quality, it is also essential to scrutinize their role in the green energy transition.

1.3 Overview of OECD economies

The Organization for Economic Co-operation and Development (OECD) has 38 member countries, which are mainly from North America, Europe and the Asia-Pacific region. These countries are known for their highly developed economies with a high human development index (HDI) and have a democratic system of government as well as a market economy. The OECD countries in total had a GDP growth rate of 2.5% on average in 2023, probably the result of a gradual recovery from the COVID-19 pandemic. Nevertheless, the growth rates are different, where the growth rate of the USA reached 2.6% and that of the Euro area slightly exceeded 2.3% (OECD, 2023b). In addition, OECD countries are at the forefront of energy efficiency improvements and green energy adoption. Taking renewable energy generation as an example, the percentage of electricity production from renewable sources in 2023 was 29%, which is higher than that in 2020 (24%), (IEA, 2023). Denmark and Germany are famous for their large shares of wind and solar energy, respectively. As shown in Figure 1, Iceland remains at the top of the list, accommodating 88.9% of the country's energy supply from renewables. Moreover, education and training are essential investments in these economies. Education will account for 1% of GDP in 2022, which is substantially lower than that of Nordic countries such as Sweden and Norway (OECD, 2023a). The labour market participation rate in OECD countries was 72.3% in 2023, which proves that workforce and adaptability skills are being developed (OECD, 2023c).

Figure 1: Green energy supply in OECD economies in 2019–2021



Source: OECD (2024a)

1.4 Research objectives

This study aims to delve into the following specific objectives. Firstly, we intend to examine the influence of countries' risk factors, including political risk, financial risk and economic risk, on green energy adoption. The stated factors are widely investigated in the context of environmental sustainability. However, their role in the transition towards clean energy has been described insufficiently. Therefore, it is essential to examine their role in green energy adoption. The prime reason for selecting these three risk factors is to offer comprehensive nuances, which could help practitioners construct effective policies.

Secondly, we aim to examine the impact of human capital development on the green energy transition. Human capital is essential for driving overall economic growth and expansion. Its criticality cannot be ignored in the green energy transition process of the OECD region. It is well known that the level of education and skills in these developed economies is greater than that in other economies. Therefore, human capital could also be essential in the transition towards green energy.

Thirdly, this empirical work delves into the impact of economic progression on the green energy transition. According to the environmental Kuznets curve (EKC) theory, an increase in income significantly contributes to the adoption of environmentally friendly energy sources. Therefore, we consider the role of economic growth in this model, as the OECD economies have established their industrial sectors, which consequently leads them to greater economic growth.

Finally, we intend to consider the role of environmental factors, including environmental technologies and energy efficiency, in the green energy transition of OECD economies. Similar to risk factors, these variables are essential for reducing environmental pollution. However, to examine their effectiveness in the green energy transition, it is essential to consider them in the research model. By fulfilling these objectives, we seek to identify key determinants of and elucidate the processes underlying the green energy transition and, in addition, provide empirically derived and current policy and strategy implications on the directions and recommendations for more progressively promoting the deployment of green energy through strategies and policies within OECD economies.

1.5 Significance and contributions

This research contributes to the literature by offering a holistic understanding of the interactions among risk indicators, human capital, economic growth, environmental technologies, energy efficiency and the green energy transition. By examining these components in the specific context of OECD economies, this research contributes to building theoretical and empirical knowledge on sustainable energy development. By investigating whether risk factors, human development, economic expansion, environmental technologies and energy efficiency are related to the green energy transition, this research has important implications for policymakers, businesses and stakeholders interested in accelerating the transition to green energy technologies and equitable development in general. Overall, this research furthers the academic literature related to the topic of green energy transition and provides practical implications for addressing global energy and environmental challenges.

2. Literature Review

Concerning the factors influencing environmental quality, numerous studies have provided empirical evidence and asserted that the key driver of ecological deterioration is the rapid consumption of fossil (nonrenewable) energy (Bergougui, 2024; Ghorbal *et al.*, 2024; J. Wang and Azam, 2024). However, to resolve this issue, scholars have recommended a transition towards green energy sources (H. X. Li *et al.*, 2020), as most empirical evidence supports the stance that green and clean energy significantly reduces environmental degradation without harming economic growth (Adams and Acheampong, 2019; R. Li and Wang, 2023). Therefore, this section discusses the essential factors influencing the green energy transition in the available literature.

Recently, the role of risk factors, governance and institutions has gained significant importance for green/clean/renewable energy promotion, transition and a cleaner environment. For instance, Uzar (2020) investigated the importance of institutional frameworks and their impact on clean energy use for developed and emerging economies from 1990 to 2015. The findings of the study reveal that an improved institutional framework boosts green energy use. Similarly, Sequeira and Santos (2018) offered a review of the connections between politics and green energy since 1980, covering the investigations of 850 studies. The research concluded that better governance and energy prices are significant political and policy determinants of green transition. More recently, Xiao Gu *et al*. (2024) examined China over the period 1984–2022 by employing several econometric tests and concluded that political risk, along with green electricity output, significantly enhances the green energy transition in the region. Furthermore, stable democratic systems may channel more investments into clean energy. In contrast, Gatzert and Kosub (2017) scrutinized the policy risk determining factors of green energy for EU economies. The primary outcomes demonstrate that policy and regulatory risks are essential for investment in green energy, particularly in industrialized regions. Burke and Stephens (2018) studied the future of clean energy and the politics of power. The findings highlight that democratic performance accommodates green energy promotion. Adebayo *et al*. (2023) also studied the role of various risk factors in the green energy transition and asserted that although political risk has an adverse influence on green energy, economic risk and financial risk significantly enhance the green energy transition, which ultimately reduces environmental hazards. In contrast, Z. Wang *et al*. (2023) revealed that reducing both financial and political risks significantly enhances the green energy transition while reducing environmental degradation. Mahjabeen *et al*. (2020) investigated the importance of institutions behind clean energy. The research concluded that durable institutional frameworks are a prerequisite for transforming the economy from conventional energy into clean and green energy and protecting the environment. Bourcet (2020) confronted green energy determinants by using a systematic literature review. The research concluded that in addition to energy security and income, a regular system is vital for explaining green energy.

Concerning the role of economic progress in the energy transition, Xiao Gu *et al*. (2024) used FMOLS, DOLS and CCR and demonstrated that economic growth and energy sector investments significantly reduce the green energy transition in China. In the MINT region, Adebayo *et al*. (2023) employed the CS-ARDL approach and reported that economic progress is hazardous for the promotion of a green energy transition, which is the key barrier to attaining environmental sustainability. Lawal (2023) investigated the influence of economic development and other socioenvironmental factors on green energy in selected African countries. Employing the GMM panel approach, the results revealed a significant constructive link between growth and green energy and the author also proposed a feedback hypothesis among the variables. Yang and Song (2023) also explored this relationship in terms of the important factors of human development and investment. The results revealed that energy efficiency and green energy use are positively correlated with economic growth but negatively linked with FDI and human capital. In a novel study, Chu *et al*. (2023) probed the factors affecting green energy and highlighted energy security and economic complexity as primary mechanisms. They employed panel techniques to identify the top 23 high energy-consuming economies. The results showed that economic complexity is more negative for higher quantiles than for lower quantiles. Energy security is positively correlated with green energy in both lower and higher quantiles. Similarly, Iqbal *et al*. (2023a) examined determinants of green energy generation in Pakistan, including the impact of economic expansion. The results revealed an optimistic connection between economic expansion, pollution emissions, financial growth and the increase in the generation of green energy in Pakistan. Additionally, Iqbal *et al*. (2023b) found a positive association between economic expansion and green energy use in Pakistan. Mohamed Yusoff *et al*. (2023) discovered a bidirectional connection between economic progression and clean energy in Malaysia. When pollution emissions decline, the deployment of clean energy technologies increases with time. Moreover, Ahmad *et al*. (2023) noted that economic expansion, country risk and energy transition have a causal relationship, with economic expansion and country risk Granger-causing energy transition.

An investigation by J. Li *et al*. (2020) on the impact of eco-innovation on green energy in OECD economies revealed that environmental innovation has a constructive impact on the implementation of green energy while reducing fossil fuel dependency. Similarly, Su *et al*. (2020) noted that technological development has the effect of preventing environmental pollution in the USA. Umar *et al*. (2020) noted that technical progression avoids pollution emissions in China. Hence, both these estimates validate the progression of these variables in enhancing the green energy transition. Alvarez-Herranz *et al*. (2017), using 17 OECD countries, found that environmental innovation plays the most significant role in green energy among other types of innovation. The authors emphasized that eco-innovation is a result of continuous R&D investments, which transform the economy from being based on nonrenewable energy to being based on a green energy system. Similarly, Su *et al*. (2021) analysed OECD economies from 1990–2018 and employed the CS-ARDL approach. The results revealed an optimistic and significant influence of environmental technologies on the green energy transition. With respect to the G7 economies, Khan *et al*. (2020) scrutinized data from 1995 to 2017 and concluded that both eco-innovation and human capital are significant in promoting a green energy transition.

2.1 Literature summary and research gap

Previous studies have extensively examined the elements affecting renewable energy use in various developed and emerging economies. Research indicates that political balance and government policies with supportive features are the main factors that can accelerate the transition to renewable energy potential (Apergis and Payne, 2010; Popp *et al*., 2011). Economic factors contribute not only to the adoption of renewable energy sources but also to the susceptibility of the economy to the effects of inflation and economic growth fluctuations, where the existence of an insecure macroeconomic system makes long-term investments in green technologies vulnerable to risks (Menegaki, 2011). Financial risk is an important issue, as it affects funds and payback rates for projects in renewable energy industry sources (Polzin *et al*., 2019). Moreover, human capital, which includes skilled labour and educational achievement (Aghion *et al*., 2016), is the key to the development and launching of these emission-reducing technologies. Acemoglu *et al*. (2012) stressed the role of technological advances and energy efficiency in accelerating the transition to low-carbon energy. Accordingly, these discoveries have contributed to the identification of circumstances through which the development of renewable energy is achieved across multiple economies.

While a review of all the factors that affect renewable energy use as well as their considerations has been performed, there is still a large deficit in creating a comprehensive analysis that includes all the factors previously mentioned. Most of the recent research has investigated the impact of these components separately but lacks a holistic approach since it has focused not only on the interplay between political, economic, financial and human capital elements but also on technological improvement and energy efficiency. In this way, we obtain a narrow view of the interreliance and possible solution phases or their weaknesses. The present study is designed to provide an analytical solution to the gap in the existing research through the use of an aggregated model that provides a joint examination of how political risk, economic risk, financial risk, human capital, economic growth, environmental technologies and energy efficiency affect energy production from renewable sources in OECD economies. Thus, this holistic methodology takes into account the factors responsible for the use of green energy and provides suggestions as to what mechanism could be employed to facilitate this transition.

3. Data and Methods

3.1 Theoretical framework and model

Political risk, economic risk and financial risk, as major determinants of green energy adoption, are subject to attention from a theoretical standpoint. Other political risks, including government instability and policy changes, are the main risk factors affecting the development of renewable energy fields since those risks are associated with the perception of government and policy instability and uncertainty (Butler and Joaquin, 1998). Hence, governments that tend to change their constitutions regularly mostly impair trust in regulatory frameworks and add to uncertainties whereby investors usually refrain from engaging in green energy projects. Economic risk, including inflation and growth volatility, is likewise a contributing factor to the kind of analysis used in swaying investments into renewable energy. Governments must maintain a stable economic environment to stimulate investment by increasing environmental risk and the predicted returns (Jaffe and Stavins, 1995). Financial risk, namely, the availability of capital and interest rate vulnerability, hurts the feasibility of green energy projects, as large financial risk increases the cost of capital and deters investments (Polzin *et al*., 2019). Low-risk profile financial institutions with a steady inflow of financial investments are the basis of growth and technology development for sustainable energy. Following these specifications, we assume a mixed influence of these risks in OECD economies.

Human elements that facilitate knowledge, education, skills and expertise in green energy technology development are not comprehensively observed, but they cannot be ignored. The creative energies and skilled work that are crucial to the development of renewable energy technology make up an essential input (Aghion *et al*., 2019). A well-educated labour force contributes to several frameworks – research, innovation and technology development – and the management of technological advances entails highly skilled staff; it has been identified that it is key in the shift to renewable energy (Popp *et al*., 2011). Furthermore, education and training programmes exclusively designed to help renewables reach higher penetration levels can be achieved by creating a well-educated labour force that is capable of handling the technical operations and unexpected challenges of those systems (Acemoglu *et al*., 2016). Following the above specifications, we assume a positive nexus of human capital with green energy.

The availability of financial and technical resources for investing is determined by economic growth, which causes the demand for innovation and therefore the growth of green energy. Increasing economic development has led to extensive financial capability of governments and businesses to enhance the development of renewable energy structures and research (Menegaki, 2011). Economic success contributes not only to people and organizations financing sustainable projects in the sector by increasing the ability of the economy to channel a larger share of financial resources to such green projects (York and Rosa, 2003). Moreover, economic development may also stimulate higher energy demand, which may govern increasing utilization of renewables depending on the policies in place to maintain sustainable demand for energy (Apergis and Payne, 2010). Despite greater economic growth, the OECD economies are still dependent on the expansion of the industrial sector, which uses traditional fossil fuel sources of energy. Therefore, we assume an adverse role of economic growth on green energy.

Along with climate change, technologies to control environmental pollution and clean energy efficiency are both relevant to green energy adoption. Ecotechnologies, *e.g.*, wind turbines and solar panels, increase the effectiveness and economic benefits of renewable energy sources; thus, the competition between renewable sources and fossil fuels increases (Popp *et al*., 2011).

Renewable sources such as wind, solar, hydro, geothermal and even biomass utilize the energy present in nature more efficiently and thereby decrease the overall energy consumption, increasing the supply of these renewable alternatives to meet the existing energy needs (Sorrell, 2009). As a part of enhanced efficiency, the overall environmental impact of energy use decreases, which is a green movement and promotes better coordination in the energy mix (Gillingham *et al*., 2009). Hence, technological innovations and energy efficiency measures are the major driver for the spread of clean energy to be widely accepted throughout the world. Since the OECD economies are developed in the context of technologies as well as energy efficiency, we assume positive roles of these variables in green energy.

Following the above linkages, investigation purposes and observed literature, this work considers various risk factors, including political risk (political risk index, *PRI*), financial risk (financial risk index, *FRI*) and economic risk (economic risk index, *ERI*), for green energy transition, proxied via renewable energy consumption (*REC*, as a percentage of total final energy used). Additionally, we consider human capital (human capital index, *HCI*), economic growth (gross domestic product, *GDP*, in constant US$ 2015), environmental technologies (development of environment-related technologies, *DERTI*, as % of all technologies) and energy efficiency (*ENEF*, *GDP* per unit of energy use measured as constant 2017 PPP $ per kg of oil equivalent). The regression model for estimation is presented below:

$$REC_{it} = \partial_1 + \theta_1 PRI_{it} + \theta_2 ERI_{it} + \theta_3 FRI_{it} + \theta_4 HCI_{it} + \theta_5 GDP_{it} + \theta_6 DERTI_{it} + \theta_7 ENEF_{it} + \varepsilon_{it} \quad (1)$$

The above model reveals the intercept (∂), slopes (θ) and standard error (ε) along with the cross-section and time series represented by i and t, respectively. For the study model and variables, we use several credible sources of data, including the WB (2023) for *REC* and *GDP*, OECD (2024b) for *DERTI* and *ENEF*, ICRG (2023) for *PRI*, *ERI* and *FRI* and Groningen Growth and Development Centre (2019) for *HCI*. The data cover the latest available period from 2004 to 2020 for the OECD economies.

The OECD countries are chosen for their sheer productivity and sovereign decision-making in the global dynamic economy as high-income countries with advanced manufacturing and democratic governance. These vital regions of the global economy not only determine international economic standards and contribute more than 60% of the world GDP but also more than 75% of the global trade. Their strategies, ideas and inventions encourage matters in the economic and environmental spheres on a global scale. Developed OECD countries carry great responsibility for the delivery of the sustainable development agenda via large investments in green technologies and the establishment of a regulatory framework for renewable energy, providing directional initiatives for lowering carbon emissions. They are the endowments of global sustainability by executing technological updating activities, cooperation among countries on climate policies and taking aggressive targets for protecting the environment. Basically, the main source of their impact comes from the fact that they are successful in integrating economic development and environmental conservation, thereby using their financial resources, technology and policy impact to lead the world in the shift from a traditional to a green economy.

3.2 Empirical methods

When inspecting a panel dataset, the first step in this process is to carry out a descriptive assessment; then, normality checks are performed on each of the components. We evaluated the median, mean and range (lowest and highest) of each variable considered in the panel data. The standard deviation of the data was calculated by statistical methods to determine how much dispersion exists due to the change in observation values over time. Additionally, to assess the normality of the data, we used kurtosis and skewness. It must be noted that this latter point is only the first step towards the main phase of the process, which is the actual construction of the model upon which the economic hypothesis is based.

In addition, we carried out two tests of diagnostic analysis, namely the cross-sectional dependence (CD) test (Pesaran, 2021) and the slope coefficient heterogeneity (SCH) test (Hashem Pesaran and Yamagata, 2008), before performing the stationary analysis. In addition, if such analysis remains overlooked, this may lead to improper adaptation of estimation methods and misleading results (Wei *et al.*, 2022). The CD test works on the following specifications:

$$\mathrm{CD}_{Test} = \frac{\sqrt{2T}}{\left[N\left(N-1\right)\right]^{1/2}} \sum_{i=1}^{N-1} \sum_{k=1+i}^{N} T_{ik} \tag{2}$$

The equation gives an idea of the CD between variables while presuming cross-sectional dependence as H_0. However, the SCH test delivers both SCH and adjusted SCH statistics, which work on the specifications given below:

$$\hat{\Delta}_{SCH} = \sqrt{N\left(2k\right)^{-1}}\left(N^{-1} \;\; -\mathrm{K}\right) \tag{3}$$

$$\hat{\Delta}_{ASCH} = \sqrt{N}\sqrt{\frac{T+1}{2K.\left(T-K-1\right)}}\left(N^{-1} \;\; - \;\; \mathrm{K}\right) \tag{4}$$

In this test, slope homogeneity is presumed to be H_0. These tests serve the objective of assessing whether the relationships among elements within groups differ from one another, apart from checking whether an area is economically interdependent on adjacent regions. Introducing slope heterogeneity as a model factor requires the approach to be quite robust, while for panel data analysis, it is necessary to take cross-sectional dependence into account to generate unbiased estimates.

After the panel data diagnostic analysis, for each chosen parameter, a unit root test is needed. We utilize different unit root test processes, such as those introduced by Phillips and Perron (1988; PP), Breitung (2000; Br), Im *et al*. (2003; IPS) and the ADF-Fisher (ADF) test (Maddala and Wu, 1999); additionally, Levin *et al*. (2002; LLC), both level [I(0)] and first difference [I(1)] information, are included in the tests of stationarity. All of these tests assume that there is a unit root. Among these tests, we should mention the presence of some of the stationarity tests, whose main purpose is to test whether the time series variable has a mean and variance that is constant through time. Stationarity must be given specific attention; otherwise, we might consider a nonstationary series, which will lead to a false regression.

After the stationarity test, we carried out a cointegration analysis by employing the residual cointegration test for the panel (Kao, 1999). This methodology was used to verify the occurrence of long-term stable associations between the study variables. Its specification assumes that the null prediction is "no cointegration between variables". These cointegration tests help establish whether the variables that are not stationary have a long-run equilibrium relationship. Cointegration is a requisite for giving validity to the fact that the variables have moved proportionally over time, which in turn will allow the multistep regression model to provide statistically acceptable results.

To comprehend the particular influence of each regressor, we employ fixed effect (FE) and random effect (RE) estimators. We use both these estimators on the panel under consideration, assuming no slope heterogeneity (the slope coefficients are homogenous across the panel). This permits us to apply both these estimators. Furthermore, the FE estimator is used to control for variables that are constant across time to analyse the effect of variables that have constant values across time. The FE model eliminated the omitted variable bias by estimating that portion of variation within the group across time. However, the RE estimation model was used for the time-invariant variables across the model. We also used the specification test (Hausman, 2015), which reveals the difference between the efficiency of the FE and RE estimators based on the specification of each model. Moreover, this investigation also tested the model authenticity. In this sense, we use linear regression with heteroskedastic panel-corrected standard errors, which offers efficient estimates while accounting for SCH and CD issues. Heteroskedasticity and autocorrelation considerations in panel models are the issues addressed by the latter. Both scenarios, if not managed properly, threaten the accuracy of the test. With the collaboration of heteroskedastic panel-corrected standard errors, we can expect more robust standard errors and more confidence in the results of hypothesis testing and confidence intervals. Furthermore, this will be ensured by accounting for panel heteroskedasticity as a random nature of the error terms.

4. Results and Discussion

4.1 Interpretation

The empirical analysis of the data is described in this section, which starts with a summary of the panel information; the outputs are described in Table 1. In this sense, we find that the mean and median estimates are positive, indicating progression of various economic, energy and risk factors in the selected period. Nevertheless, there is very little difference in the mean and median statistics. However, a significant difference was observed in the highest and smallest values of the variables. As a result, the standard deviation is the highest for the *GDP*, followed by the *REC*. To determine the normality of the panel information, skewness and kurtosis are evaluated. Both metrics indicate nonnormality in terms of skewness and peakedness.

Table 1: Descriptive statistics

	DERTI	***ENEF***	***ERI***	***FRI***	***GDP***	***HCI***	***PRI***	***REC***
Mean	1.010302	0.030147	1.586120	1.574597	11.72335	0.492988	1.892295	1.208530
Median	1.018910	0.034829	1.593150	1.565505	11.65635	0.511319	1.904110	1.218840
Maximum	1.269980	0.133977	1.684990	1.685370	12.66190	0.568516	1.971590	1.786120
Minimum	0.688420	−0.103835	1.423250	1.444570	11.03790	0.318404	1.644270	0.305781
Std. dev.	0.114853	0.046575	0.051607	0.052588	0.400795	0.060472	0.063177	0.354184
Skewness	−0.413588	−0.301827	−0.496611	0.095668	0.614468	−1.170733	−1.882173	−0.252071
Kurtosis	2.815299	3.013183	3.047686	2.622712	2.928529	3.571080	6.972461	2.299121

Note: Authors' own calculations
Source: Authors' own calculations

After summarizing the data, we utilize several diagnostic measures to evaluate heterogeneity as well as cross-sectional dependency of the variables. In this regard, the slope heterogeneity (Pesaran, 2021) outcomes are shown in Table 2. The statistical values for *SCH* and $SCH_{adj.}$ are highly significant ($p < 0.01$). Consequently, H_0 for the test must be neglected and slopes heterogeneity is validated.

Table 2: Slope homogeneity

Test	Delta	Pr.
SCH	5.537***	0
SCHadj.	8.072***	0

Note: *** indicate that statistical values are significant at the 1% significance level, respectively.
Source: Authors' own calculations

Next, we intend to examine the CD between the variables for which the specifications of Hashem Pesaran and Yamagata (2008) are used and for which the results are described in Table 3. All the variables exhibit highly significant values, with $p < 0.01$ for the study variables. Therefore, the test H_0 may be neglected and it is decided that CD persists among the variables.

Table 3: Cross-sectional dependence

Variable	CD test	Pr.
REC	24.010***	0
GDP	19.232***	0
DERTI	18.112***	0
HCI	39.029***	0
ERI	13.947***	0
FRI	13.040***	0
PRI	18.567***	0
ENEF	26.356***	0

Note: *** indicate that statistical values are significant at the 1% significance level, respectively.
Source: Authors' own calculations

A panel dataset must be stationary if the analysis of the coefficient values is aimed at the variables of interest. We employ a series of stationarity tests and the estimated results are described in Table 4. We note the diverse nature of the variables, where several tests validated stationarity, while others identified the presence of a unit root for variables at I(0). Specifically, the variables *REC*, *DERTI*, *ENEF*, *ERI*, *FRI*, *GDP* and *PRI* are significant at LLC and PP most of the time.

However, the results are mostly insignificant across the other stationarity tests. Therefore, we test all the variables at I(1). The significance level of the variables is noted to be higher for all the tests at $p < 0.01$, 0.05 and 0.10. Therefore, H_0 must be neglected and it is decided that all the variables are stationary for use in the cointegration analysis.

Table 4: Stationarity testing

Panel unit root test: summary [I(0)]								
Method	***REC***	***DERTI***	***ENEF***	***ERI***	***FRI***	***GDP***	***HCI***	***PRI***
LLC	−2.484***	−2.758***	−2.572***	−3.836***	−2.254**	2.463	6.501	−1.956**
Br	3.741	0.374	−0.032	−3.479***	−0.052	−2.750***	14.964	−1.385*
IPS	0.545	−0.453	−0.021	−0.635	0.706	−1.800**	8.120	0.255
ADF	27.764	31.598	24.817	29.905	20.745	32.679	9.361	23.084
PP	48.381***	56.513***	38.528*	35.815	52.778***	14.269	9.066	9.233
Panel unit root test: summary [I(1)]								
LLC	−11.769***	−1.072	−6.189***	−7.756***	1.263	−1.461*	−43.096***	−5.809***
Br	−7.463***	−5.511***	−9.095***	−8.948***	−3.747***	3.573	−18.002***	−7.107***
IPS	−9.140***	−2.783***	−5.187***	−4.807***	−1.358*	−1.650**	1.669	−4.022***
ADF	119.627***	52.134***	76.868***	73.388***	31.583	38.124*	9.781	60.782***
PP	185.029***	182.868***	205.196***	148.643***	239.860***	32.0388	78.732***	89.069***

Note: ***, ** and * indicate that statistical values are significant at the 1%, 5% and 10% significance level, respectively.

Source: Authors' own calculations

The scientific results for the cointegration test are obtained via the Kao residual test (Kao, 1999) and are presented in Table 5. The results show that the differences are significant ($p < 0.01$). Due to such significant estimates, H_0 can be disproved and it is determined that the considered variables have a stable cointegration connection between them. Such a significant analysis permits us to examine the specific impact of each regressor on the *REC*.

Table 5: Cointegration results

Kao residual		
ADF	***t*-stats**	**Pr.**
	−4.758***	0
Residual variance	0.001	
HAC variance	0.001	

Note: *** indicate that statistical values are significant at the 1% significance level, respectively.
Source: Authors' own calculations

In the context of the long-run coefficient, we use fixed effect and random effect estimators and the empirical outcomes are described in Table 6. We reveal the diverse influences of various regressors on the *REC*. The *DERTI*, *PRI*, *HCI* and *ENEF* play significant roles in enhancing the green energy transition. Among these variables, the magnitude of the impact is greater for the *ENEF* and *HCI*. The significance level for these variables is noted to be higher, where $p < 0.01$, 0.05 and 0.10. Additionally, these estimates are in line with the results of Xiao Gu *et al*. (2024), Khan *et al*. (2020), Sequeira and Santos (2018) and Yang and Song (2023) for various panel and time series analyses. However, there are economic and risk factors such as *GDP*. The *FRI* and *ERI* adversely influence the *REC* in the long term. Among these variables, the greatest adverse impact is noted for the *FRI*, followed by *GDP* and the *ERI*. The significance for these variables is noted as $p < 0.01$ and 0.10. However, these findings are not unique but are consistent with the empirical results of Ahmad and Zheng (2023), Chu *et al*. (2023) and Umar *et al*. (2020), which contradicts the findings of Khan *et al*. (2020) and Su *et al*. (2021), as these studies identified the progressiveness of eco-innovation in green energy for various economies.

Table 6: Long-run results

Variable	FE		RE	
DV: *REC*	Coef.	Std. er.	Coef.	Std. er.
GDP	−0.965***	0.089	−0.721***	0.044
DERTI	0.060**	0.021	0.064	0.038
PRI	0.280***	0.061	0.300**	0.119
FRI	−1.313***	0.370	−1.453***	0.488
ERI	−0.188*	0.103	−0.158*	0.081
HCI	3.277***	0.650	3.138***	0.394
ENEF	5.079***	0.843	4.544***	0.513
Cons.	12.532***	0.469	9.882***	0.334

Note: ***, ** and * indicate that statistical values are significant at the 1%, 5% and 10% significance level, respectively.

Source: Authors' own calculations

To compare the statistical outcomes of the FE and RE methods, we use the Hausman test (Hausman, 2015) with the H_0 "RE is appropriate" until the statistical values are significant. The statistical value of chi^2 is greater than the corresponding critical value. Therefore, H_0 can be neglected and the fixed effect estimator is appropriate for the analysis of the panel data under consideration.

Table 7: Hausman test

DV: *REC*	FE (Coef.)	RE (Coef.)	Difference	Std. er.
GDP	−0.965***	−0.721***	−0.245	0.077
DERTI	0.060**	0.064	−0.004	–
PRI	0.280***	0.300**	−0.020	–
FRI	−1.313***	−1.453***	0.140	–
ERI	−0.188*	−0.158*	−0.029	0.064
HCI	3.277***	3.138***	0.139	0.517
ENEF	5.079***	4.544***	0.535	0.669
Cons.	12.532***	9.882***	−0.245	0.077
Chi^2	126.09***			

Note: ***, ** and * indicate that statistical values are significant at the 1%, 5% and 10% significance level, respectively.

Source: Authors' own calculations

Concerning the robustness test of the considered model, we employ a novel "linear regression with heteroskedastic panel-corrected standard errors" and the results are reported in Table 8. The results demonstrate a similar influence of each regressor on the *REC*. The positive and significant influences of the REDTI, *PRI* and *ENEF* are shown. However, the *HCI* is insignificant. Nevertheless, its positive correlation with the *REC* validates the progressive role of the variable, as discussed above. In contrast, this test shows that the *GDP*, *FRI* and *ERI* have an adverse influence on the *REC* of the selected economies. Such positive and negative influences of these variables are consistent with the empirical outcomes obtained via the fixed effect and random effect estimators and the empirical outcomes of Burke and Stephens (2018), Gatzert and Kosub (2017), Iqbal *et al*. (2023a) and Khan *et al*. (2020).

Table 8: Robustness analysis via heteroskedastic panel-corrected standard errors

Variable	Coef.	Std. er.	z	Pr.
GDP	−0.486***	0.035	−13.860	0.000
DERTI	1.385***	0.161	8.620	0.000
PRI	2.061***	0.314	6.560	0.000
FRI	−1.310***	0.434	−3.020	0.003
ERI	−3.475***	0.572	−6.080	0.000
HCI	0.048	0.308	0.160	0.876
ENEF	1.128***	0.369	3.050	0.002
Cons.	1.823**	0.775	2.350	0.019

Note: ***, ** and * indicate that statistical values are significant at the 1%, 5% and 10% significance level, respectively.

Source: Authors' own calculations

4.2 Discussion

The findings of this research underscore the intricate interplay between multidimensional economic and risk factors and their nexus with the green energy transition in OECD economies. Although economic growth is generally considered a catalyst for development, it showed a significantly negative association with the green energy transition. This result may be due to the trade-off between economic expansion and environmental sustainability. For instance, Sovacool (2016) reported that there is a decoupling challenge for advanced economies to detach economic growth from carbon emissions. The paradoxical negative relation between economic growth and the green energy transition in OECD economies may also manifest the dilemma of shifting from deeply entrenched energy systems overwhelmingly reliant on fossil fuels. In fact, Dietz and Stern (2015) purported that the concept of carbon lock-in entails the carbon present and future emission inflows that are built into the current economic system, infrastructures and life practices of the fossil fuel scale growth economy. Consequently, the blueprint for carbon-based energy systems makes it stressful for niche innovations to displace entrenched regimes. Thus, inculcating systemic transformative reconfigurations in the modes of energy production and consumption is imperative to promote the green energy transition.

Moreover, the highly significant adverse effects of the financial risk index and economic risk index on the green energy transition underscore the need for stable financial conditions to encourage sustainable investments in switching to renewable energies. The inference that economic and financial viability are indispensable enablers for attaining renewable deployment has previously been shared in the literature by Stern (2007) and Löffler *et al*. (2017). Furthermore, these premises support the vulnerability of renewable energy investments to economic vagaries and market caprices. In contrast to O'Brien *et al*. (2010) and Linnerooth-Bayer and Hochrainer-Stigler (2015), there is an enduring consensus that policy stability, regulatory prudence and financial support are essential for ameliorating investment hazards and aligning capital streams with sustainable energy ventures.

Conversely, the results illustrate that the positive effects of environmental technologies, the political risk index, the human capital index and energy efficiency on the green energy transition all stem from their capacity to alleviate critical barriers and boost sustainable development. Firstly, environmental technologies are pivotal in facilitating the uptake of clean energy sources and reducing greenhouse gas emissions. Advances in renewable energy generation, energy storage and smart grid technologies have rendered green energy solutions more feasible and competitive. Wen *et al*. (2021) proved that environmental innovation is pivotal in promoting sustainable development agendas by ushering in energy-efficient and ecologically sound alternatives to traditional energy sources.

Secondly, political stability and enabling regulatory environments, as reflected in the political risk index, are crucial to attracting capital and catalysing innovative capacity in green energy. Markets operating under stable political conditions can be used to devise long-term strategies and offer incentives that attract renewable energy investments. Becker (2023) noted that the value of political stability lies in triggering private sector investments in clean technologies via policy predictability.

Thirdly, human capital – marked by a skilled and educated workforce – paves the way for technological innovation and sustainable development. A high human capital index indicates that the population is armed with the knowledge and expertise to drive the green energy transition by research, development and implementation of environmental technologies. Khan *et al*. (2020) underscored a positive relationship between the development of human capital and the nurturing of green innovation and highlighted the role of education and training in building a sustainable workforce.

Finally, energy efficiency makes an ideal complement to the green energy transition by optimizing the use and reducing the overall consumption of energy. Improvements in energy efficiency across sectors lead to lower carbon emissions and enhance the economic viability of renewable energy projects. Chapman and Itaoka (2018) pointed to the synergies between energy efficiency improvements and the deployment of renewable energy, indicating the potential to build integrated solutions that deliver a sustainable energy transition.

5. Conclusion and Policy Implications

Our analysis of the dynamics of the green energy transition within OECD economies between 2004 and 2020 provided key insights into the drivers of the green energy transition. The fixed effect and random effect estimators highlighted significant associations between green energy transition and a range of variables. The negative effects on the green energy transition arising from economic growth, as well as from the financial risk index and the economic risk index, underscore the challenges posed to the green energy transition by economic uncertainties and financial instability. The positive effects of environmental technologies, the political risk index, the human capital index and energy efficiency on the green energy transition reveal the importance of technological innovation, political stability, a skilled labour force and energy conservation to the generation and adoption of sustainable technology pathways. This finding points to a complex interplay of economic, political, technological and human capital factors driving green energy. A comprehensive green energy transition would require a holistic strategy that addresses the combination of barriers and enabling factors observed throughout the analysis period 2004–2020. By understanding the multifaceted interrelationships between these variables, policymakers, businesses and stakeholders will gain additional insights into the development of targeted interventions and policies for transport and diffuse green energy technologies and associated risk management strategies.

5.1 Policy implications

Our findings have several important implications for policymakers seeking to accelerate the green energy transition in OECD economies. Firstly, the development and deployment of environmental technologies could be useful for attaining a sustainable energy transition. Policies that facilitate the development of cleaner technologies, possibly through R&D incentives and technology adoption and diffusion incentives, should be developed. Secondly, political stability and clear regulatory frameworks that facilitate investment and innovation in green energy are crucial for developed economies. Policymakers should reinforce stable and supportive regulations. In addition, policy signals may be necessary to stimulate investment in integrated renewable energy projects by creating consistent policies to reduce the uncertainty of investment and barriers to the development of renewable energy projects. Thirdly, human capital development and educational policies designed to develop a workforce to drive green innovation and technology adoption should be supported. Specifically, policies should be aimed at increasing the levels of education, training and capacity in areas closely aligned with renewable energy and environmental sustainability. Finally, the development of new technologies and approaches will improve efficiency. Policymakers should also promote energy-saving behaviour and development and application of energy-saving technologies by utilizing efficiency measures to optimize green technology utilization and reduce carbon emissions. If policymakers can inseminate these policies and advocate the insights provided by this analysis, these economies will create a smart way to accelerate towards a low-carbon sustainable future and to promote economic growth and development, environmental protection and a sustainable transition towards green energy.

5.2 Study limitations and future research directions

Several limitations of this comprehensive research must be noted. Firstly, it could raise doubts concerning the validity of the output for OECD countries only, although they are economically diversified and largely heterogeneous in terms of their governance and policy structures. Another reason for the advantage of panel data techniques is that they disregard a wide range of problems, such as structural breaks, and fully consider dynamic changes. Another relative limitation is the concern about the data constraints that may hamper the accuracy of the results. This may also occur when there is an absence of basic or essential factors that need to be studied in the process of assessing the factors that influence the adoption of renewable energy. Therefore, traditional econometric methods may not be sufficient to address this problem as complexity increases, as there may be potential endogeneity between the selected variables.

The future outlook should, however, eliminate the limitations associated with not including non-OECD countries in the analysis. This approach will provide more accurate and comprehensive results. By adding more disaggregated data, for instance, the shift towards clean power consumption in specific sectors would be taken as a case study in the theoretical background, which would serve as a real consumer behaviour guideline system. Another experimental design method worth mentioning is the use of dynamic panels or structural equation modelling (SEM) as a research strategy. Through these methods, many complex interactions among the variables can be discovered, and thus, a paradigm for the object of study can be found. In addition, long-term politics and technological revolution in the context of the green energy transition should not be ignored. As such, future analysis in the same field of research should focus on their impacts to clearly determine their role in the clean energy transition.

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