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Traversing Innovation and Environmental Sustainability Nexus: Mediating Role of Energy Forms in High Energy Economies

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Abstract

The concerns about environmental degradation are exacerbated by hikes in energy consumption. The innovations amplification effect the environment while energy sources effect both negatively. This study investigates the detrimental role of energy forms (mediation Effects) in technological innovation and the environmental nexus. The research uses a sample of 23 economies with the highest energy consumption globally from 1990 to 2020. The seemingly unrelated regression (SUR) model has been used to explore the innovation and environment nexus. The study shows both positive and negative mediating effects of non-renewable and renewable energy use. Additionally, it highlights a simultaneously adverse direct impact of innovation on the environment, adding to a more complex comprehension of the complex relationship between ecological sustainability and technological advancement. The findings emphasize the significance of considering various routes of influence while evaluating the environmental implications of technological advancement. The findings of the study provide evidence for the emphasis of technical innovation in improving environmental performance. Further, it emphasizes the significance of renewable energy usage in mitigating environmental degradation. Policymakers should provide incentives to research and development in technical innovations. However, giving priority and subsidy for the adoption of renewable energy sources can help enhance environmental performance and mitigate environmental degradation.

Keywords: *Mediation Effects, SUR Model, Technological Advancement, Environmental Degradation*

JEL Classification: *O31, Q55, Q43*

1. Introduction

The Environment is poised of biodiversity, natural resources, and ecosystems, which exist in delicate balance for life on Earth. However, increasing population along with technological footprint have greatly influenced the environment. Therefore, concerns about sustainability and preserving our planet's natural resources have risen recently. Since the late 19th century, the Earth's surface temperature has raised by an average of 1.2 degrees Celsius, with most hike occurred in the last four decades (NASA). Further, the Intergovernmental Panel on Climate Change (IPCC) has predicted that if global warming keeps its pace, it will probably exceed 1.5 degrees Celsius between 2030 and 2052.

The rising strain that human exploitation of products and services is placing on ecosystems is causing ecological distortions, climate change, environmental degradation (ED), and economic failures (Destek & Sarkodie, 2019). The environment is impacted by increased human activity both directly and indirectly. These effects are influenced by population growth, energy use, and economic expansion. According to Danish and Wang et al. (2017), energy consumption has a negative influence on environmental quality; however, the impact may vary depending on the proportion of overall renewable (REC) and non-renewable energy consumption (NREC). These RE sources, which are plentiful and have a much smaller environmental impact than NRE resources, include sunshine, rain, wind, waves, and heat. In contrast, energy that comes from limited resources that are not easily replaced quickly is referred to as non-renewable energy. Fossil fuels such as natural gas and coca oil are examples of non-renewable sources. Non-renewable energy sources play a major role in the rise of greenhouse gas emissions and air and water pollution. Even though they significantly increase CO2, transportation and energy generation rely on burning NRE sources such as coal, oil, and natural gas (Phong 2019; Raza et al 2015). All nations must switch to alternative energy sources, like more renewable and cleaner energy, in order to address the global pollution issue.

More specifically, some empirical researchers (Dogan et al., 2016) have discovered that the use of NREC exacerbates ED while the use of REC improves it (Danish et al., 2017). These researchers stressed the significance of switching from fossil fuel-based conventional energy sources (like oil, coal, and gas) to renewable energy sources (RES) (like solar, hydropower, and wind) because the use of fossil fuels degrades environmental quality. Charfeddine and Kahia (2019) added that developing RES can aid a nation in mitigating environmental harm.

However, based on certain empirical research (Menyah et al., 2010; Pata, U.K. et al., 2021), using RES might only slightly affect ED. According to (Menyah and Wolde-Rufael at al. 2010), using RES may not be able to stop ED until they account for a sizable fraction of all energy use. However, the percentage of different energy sources in any economy depends on the degree of technical progress. In order to achieve sustained environmental quality, technological innovation (TI) can be extremely important. Technology's impact on the environment has long been a topic of discussion, with some arguing that it has a beneficial or detrimental effect. Reducing our dependency on fossil fuels and emissions are two ways that certain technologies, such as pollution control and RE, might benefit the environment (IPCC). Some technologies, on the other hand, can be harmful to the environment. Examples include electronic trash and some types of genetic engineering (IPCC).

The technology and environment nexus has been explored in a number of studies. Research has examined the role of the patent as a representation of innovations (Mensah et al 2019). The relationship between TI and CO2 emissions has been explored in the literature from a number of angles. However, there is disagreement regarding how important TI is for lowering carbon emissions (Lindman et al., 2016). Depending on the countries, study variables, and methodological details, the results of the literature vary greatly. While some studies (Wang et al., 2016; Hermwille et al., 2017; Green, 2018) find that innovations play the expected role, others (Hodson et al., 2018) find that innovations have no effect on emissions or even increase them (Su et al., 2021).

Nevertheless, the environment is also greatly impacted by the large energy using economies. They are significant producers, consumers, and emitters of greenhouse gases. Therefore, their portion of the world's greenhouse gas emissions, which fuel climate change substantially. Additionally, they use a significant portion of the world's natural resources, including gas, coal, and oil (IEA 2022). The availability of inexpensive RES must be considered to achieve SDG-7 (Elsayed et al., 2021). Employing RES is crucial to increasing the world's energy mix. High-energy consumers are, in this sense, undertaking bold plans to enhance RE.

Figure 1 and Figure 2 show the trends in the use of REC and NREC, respectively, for selected economies from the sample. Throughout the time period, the graph shows an overall upward trend in the use of RE in each of the ten countries. The upward trend is an evidence of the increasing magnitude in energy mix of these economies. This further implies that the need for RES to meet energy demands is expanding. Although every country experiences an upward trend, each has a different growth rate. As compared to other countries, the percentage of REC in Denmark, Norway, and New Zealand is increasing at a sharper rate and substantially higher in 2021. Conversely, the economies like United States, Poland, and Italy show a steadier and slower development.

The graph analysis points to a global shift in the usage of RE. However, the rate at which this shift occurs varies by nation, with some reaching a significantly greater reliance on renewa ble sources than others.

Figure 1: Renewable energy use in High Energy using Economies (Author Estimates)

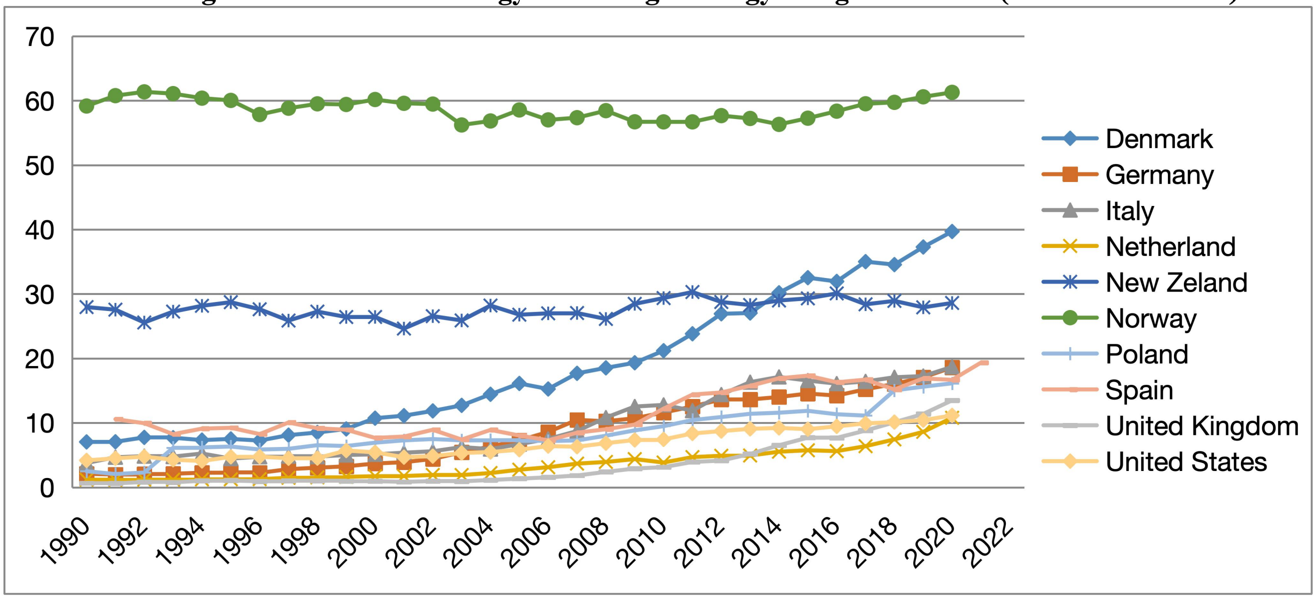
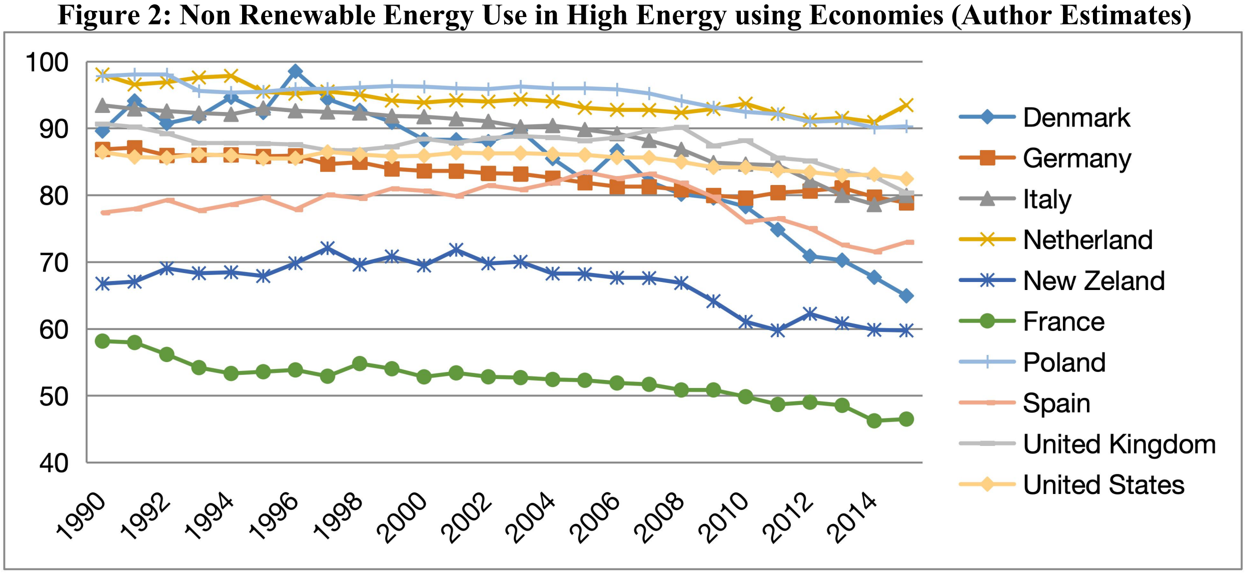


Figure 2 exhibits the NREC trend for which the information is available for the years 1990 to 2015. A negative trend toward less reliance on non-renewable energy sources (NRES) is seen. This pattern points to increased public knowledge of environmental issues and a possible shift toward more environmentally friendly energy methods. Significant progress can be observed in the steeper drop in NREC in countries like New Zealand consumption rate decreased from under 66.74% in 1990 to over 59.74% by 2015, and Denmark consumption rate decreased from under 89.59% in 1990 to over 64.92% by 2015. Conversely, nations like Poland or Spain, depicted by lines with a shorter downward slope, may be going through the change more slowly. The graph indicates a worldwide trend toward less reliance on NRES. This trend is positively indicating the direction of environmental sustainability. Nevertheless, different nations are going through this shift at different rates; some are showing a faster decline in the NREC than others.

Figure 2: Non Renewable Energy Use in High Energy using Economies (Author Estimates)



Previous research has primarily employed carbon emissions as a proxy for ED (Menyah et al., 2010; Danish et al., 2017). There is currently a lack of research on how energy use, both renewable and non-renewable, affects the environment. (Najia Saqib at al2023) makes the case that the influence of technology innovation, climate technologies, and RE considerably lowers the ecological footprint levels in emerging countries. Furthermore, in rising nations, the ecological footprint levels are greatly increased by financial inclusion and economic expansion. However, by promoting innovative technologies and minimizing ecological footprints, the integration of RE and innovative technology in developing nations lessens the negative effects of financial inclusion. For eight Asian economies, Rajesh Sharma et al. (2020) suggested that RE and ecological footprint have a negative connection; nonetheless, these nations' high population densities have resulted in a rise in pollutant emissions.

The current study, however, intends to look at the economies of high energy users and how TI impacts the environment, as well as the effects of RES and NRES. For economies with major energy use, the mediation effects of energy on economic results are more significant. High levels of energy consumption and a strong reliance on energy-intensive industries are common characteristics of these economies. They are consequently more susceptible to fluctuations in energy costs and energy-related shocks (IEA 2019). For high-energy consumers, improved economic outcomes are mostly dependent on RE. Through its effects on the environment, energy can also mediate economic results. Economic activity can be significantly impacted, both directly and indirectly, by environmental harm resulting from the production and consumption of energy. Take lower worker productivity as an example of how air pollution might raise healthcare expenditures. Infrastructural damage and interruptions to economic activity are further consequences of climate change.

In the association of above discussion the study will follow the number of objectives. It will investigate the effects of energy forms in the transmission effect of TI to the environment for high energy users' economies. It will further will further effectiveness of alternative energy sources in the transmission effect of TI to the EF for high energy users' economies. The study will also check the mediation role of alternative energy sources for nexus of technology and environment for the high energy using economies. The economies with high energy consumption are important to the world economy. They are significant emitters of greenhouse gases and significant producers and consumers of goods and services. To the best of our understanding, no studies have explored the mechanism channel of how TI affects EQ by transmitting its impact through energy consumption in the context of REC and NREC. This study aims to clarify the positive and negative impact of TI on EQ by explaining that TI can lead to increased REC or NREC and ultimately influence EQ. Therefore, we analyze the mediating role of REC and NREC in the relationship between TI and EQ.

The contributions of the current study are manifold. It first explains the environmental effects of NREC and REC for economies with large energy consumption economies. By using ecological footprint(EF), we are able to capture various aspects of ED, in contrast to previous research that usually concentrated on carbon emissions. Since it evaluates the effects of human activity on the ecosystem as a result of consumption and waste absorption, clothing's digital footprint, in contrast to carbon emissions, is a broad indicator of environmental deterioration (Rudolph, A at al 2017 and Wang, Q et al., 22). The empirical results of how direct energy use—both renewable and non-renewable—affects the ecological footprint may help shape policies that mitigate ecological issues in the economies of high-energy consumers. Furthermore, this research offers a naïve perspective by revealing the mediating function of REC and NREC in relation to the environmental consequences of energy consumers' earnings. Determining whether REC and NREC plays a major or minor mediating role in EF is essential. This study's third contribution is to demonstrate the mediating role that REC and NREC and EF have for the economics of high energy consumers by combining TI with these energy sources. The sample of high energy users' economies is another contribution. Additionally wants to delve into how technological advancements affect the environment. Economies with high energy consumption contribute significantly to the world economy. In addition to being significant emitters of greenhouse gases, they are also significant producers and consumers of products and services. Global economic growth is significantly influenced by the economies of high energy users.

Following is the sequence of the remaining sections of the study: A literature review is provided in the "Literature review" section, while the data sources, model construction, and econometric methodology is given in Section 3. In section 4, an analysis and result discussion is provided. Finally, the study is concluded in section 5.

2. Literature Review

The study aims to quantify the ecological footprint (EF) of high energy user economies by comparing the usage of renewable and non-renewable energy sources with technological advancement. Therefore, the prior research on the effects of renewable and non-renewable energy on the EF will be covered in this part.

2.1 Ecological Footprint Energy Consumption and Environmental Policy

When energy demand is initially high, especially for countries that rely on traditional energy sources, the correlation between energy consumption and ecological footprint is higher. Fossil fuel consumption is a major factor contributing to the environmental effect. The environmental Kuznets curve (EKC), as it is known in the literature, is an inverse connection that occurs after reaching a threshold level. Many supported the same findings. For example, Uddin et al. (2016) argued for the validity of the EKC hypothesis is only supported by ten countries out of the 22 economies data. It also implied that the sample countries' ecological footprints may be decreased by using clean technology and conserving energy.

Using the Markov switching model, (Charfeddine 2017) discovered that energy consumption and economic growth strongly correlate with the ecological footprint and CO2 emissions. According to (Destek 2020), there is a positive correlation between economic growth and ecological footprint in a recently industrialized economy. A study by Shahzad et al. (2020) for USA stated that the USA's ecological footprint has increased significantly as a result of economic complexity and the use of fossil fuel oil. Conversely, the quantitative causality empirical research demonstrated the existence of causal relationships between energy use and economic complexity and their ecological footprint.

Additional environmental quality indicators that have been employed in numerous studies include CO2 emissions (Naz & Kousar, 2024; Fatima et al., Zhang and Lin 2012; Bhujabal et al 2021; Yang et al 2021). Similar to this, a study by Khan and Hou (2021) investigated the relationship between energy use and ecological footprint. They discovered that these countries' energy use is eventually lowering environmental quality by using sophisticated panel techniques to analyze the data. However, a study by Sharma et al. (2021) looks into how environmental quality is affected by the use of renewable energy in eight Asian developing nations. According to their long-run estimates, renewable energy improves the quality of the environment in these nations. Life expectancy does, however, have a small but positive effect. Majeed et al, 2021 used a NARDL model. The empirical results for marginal intake indicate that only damaging shocks have a significant impact on ecological footprint. The ecosystem is also impacted asymmetrically by various forms of energy consumption.

One of the main tools the government uses to improve environmental protection is the environmental policy (Stavropoulos et al. 2018). According to Asıcı and Acar (2016), there are instances where the EFP in 116 nations is unaffected by the strictness of environmental regulations. Based on research conducted in 87 countries, Asıcı and Acar (2018) found no correlation between the stringency of environmental regulations and environmental finance per capita.

2.2. Ecological Footprint and Technological Innovation

Under various theoretical assumptions, environmentalists have mostly examined the ecological impact of financial expansion, scientific advancements related to climate change, and TI. In an effort to achieve this goal, (Zeraibi et al., 2021) investigated how financial growth and technological advancement affected ED in ASEAN nations. The primary findings suggest that technical advancements signify a decline in ecological degradation, similar to the ecological footprint observed in the candidate nations.

Innovation in technology is another important driver of economic expansion, driving green investments that are known to improve environmental performance. Motivated by the observation that the adoption of new technologies reduces ecological footprint, numerous studies have examined the relationship between TI and the environment, demonstrating that TI have raised global environmental quality by lowering anthropogenic emissions (Sun et al 2022, Tariq et al 2022, Ren et al 2022, Ahmad at al 2022).

Technology innovation favors environment, as evidenced by Chen et al. (2022). The study's findings demonstrated that 'Newly Industrialized Countries' environmental strain was reduced as a result of technological progress. Based on this hypothesis, Khan et al. (2021) investigated the efficacy of TI in reducing the adverse environmental effects of carbon dioxide emissions. TI contributes to environmental remediation, according to the authors' case study of countries involved in the Belt and Road Initiative (BRI) between 2000 and 2014. The research conducted by Lin and Ma (2022) provides more evidence that green technology innovation can effectively reduce carbon dioxide emissions by improving the industrial structure. The bootstrapped autoregressive distributed lag (BARDL) model was utilized by Suki et al. (2022) to observe that TI contributes to the decrease in Malaysia's ecological footprint in addition to lowering carbon dioxide emissions. Similar findings suggest that TI can effectively reduce ED. Zhang et al. (2022) provide evidence of this, showing how urbanization's negative environmental effects were mitigated in the BRICS countries between 1990 and 2018.

2.3 Renewable Energy Consumption and Environmental Degradation

The renewable energy includes the sustainability concerns along with other benefits. Empirical research has linked it environmental quality. (Sbia et al., 2014) identified bidirectional Granger causalities for United Arab Emirates. In addition to these findings, studies by Ben and Ben (2017), Sinha and Shahbaz (2018), and Chen et al. (2019) uncover evidence of adverse effects for Algeria, Turkey, Tunisia, India, and China, in that order.

Environmental deterioration decreases by use of renewable energy. The study by Bekun et al. argued for by using the PMG-ARDL framework across 16 EU member states. Supporting this, (Wang and Dong 2019) show that in sub-Saharan African nations, there is a negative correlation between the use of renewable energy and ecological footprint. For a group of 25 nations included in the Belt and Road Initiative (BRI), Wang et al. (2021) present opposing data. By breaking out the effects of renewable energy on carbon emissions using the Generalized Divisia Index Method (GDIM), they demonstrate that, rather than growth in renewable energy itself being a catalyst for carbon emissions, the main factor limiting carbon emissions is the intensity of carbon in renewable energy. The impact of renewable energy consumption on carbon emissions varies significantly among 120 countries, according to a global study (Dong et al., 2019) that included four sub-panels based on income levels.

2.4 Non-Renewable Energy Consumption &Environmental Degradation

Non-renewable energy sources have received more attention in the numerous studies that have examined the relationship between energy usage and environmental damage. According to Imamoglu (2018), for example, Turkey's growing ecological footprint can be attributed to its energy consumption and gross domestic product. The study by Khan et al. (2020), examines asymmetries in its assessment of the relationship between energy consumption and ecological footprint. They reveal an unequal long-run relationship among the variables taken into consideration using the NARDL model. A study by Dogan et al. (2019) shows that NREuse has a favorable effect on EDin MINT nations, the same conclusions are established by Baloch et al. (2019) for the BRI countries. This is one of the few studies that discovered a connection between nonrenewable energy use and environmental quality. Using a variety of environmental quality indicators, including carbon emissions, ecological footprints, and the robustness of each country's environmental performance levels, Ozcan et al. (2020) conclude, in particular, that the OECD countries are starting to align with different environmental policies for environmental safety.

Overall, the relationship between energy consumption and ecological footprint is strong. Countries that rely on non-renewable energy sources have a larger ecological footprint. After a certain point, there is a reverse relationship between energy consumption and environmental pollution, which is known as the Environmental Kuznets Curve (EKC) hypothesis. Studies have found that the EKC hypothesis is valid in some countries (Uddin et al 2016) 22 countries during 1961– 2011 only 10 countries valid this hypothesis, but not in others. Clean technology and efficient energy resources can be used to reduce the ecological footprint in countries that do not exhibit the EKC hypothesis. Renewable energy consumption can help to reduce the ecological footprint of a country. A study found that renewable energy enhances environmental quality in eight developing countries of Asia. Environmental policy can also help to reduce the ecological footprint of a country (Stavropoulos et al. 2018). However, some studies (Asıcı and Acar 2016) have found that environmental policy stringency has no impact on theEF. TI is another important factor that can help to reduce the EF of a country. Sbia et al., 2014 argued that environmental deterioration appears to be negatively impacted by the use of renewable energy. However, Imamoglu, 2018 argues for favorable impact.

3. Methodology and Model

This section explains the mechanism and methods of the stated objectives

3.1 Theoretical Background

The theoretical foundation covers the concepts of energy forms, TI, and ecological footprint. The supply and demand of nature can be measured via ecological footprint. From a demand perspective, the ecological footprint estimates the ecological resources required by a civilized society to produce the natural resources it consumes and manage its waste, especially carbon emissions. The ecological footprint maintains six categories of feasible surface areas: "woodlands, crops, livestock fields, fisheries, built-up land, and demand for carbon on land." A nation's biological productivity is reflected in its supply-side bio-capacity. According to Bilgili and Ulucak (2018), it takes up waste, especially carbon emissions. The term "ecological footprint" was first used by Rees (1992), however it was later expanded upon by Wachernagel and Rees (1996). TI can impact the environment both positively and negatively.

Technological progress benefits the environment (Haldar and Sethi 2022). Raihan et al. (2022) claim that TI opens the door to improved ecological performance. TI can lead to resource efficiency. Innovations like LED lighting, fuel-efficient vehicles, waste treatment technologies, electric vehicles, etc can improve the environment. Contrary, the Rebound Effect states that efficiency improvements can lead to increased consumption that can offset the environmental gains. The Jevons Paradox explains that TI often results in more efficient use of resources and reduced overall consumption. However, due to lower costs demand increased ultimately leads to an overall resource used increased. Therefore, it is expected that TI can either improve or damage the environment.

Thus, the empirical effect can be expressed in the following way:

$$\frac{\partial \mathrm{EF}_{it}}{\partial \mathrm{TI}_{it}} > \text{, or } < 0$$

In addition to being considered as a substitute for traditional energy sources, renewable energy also has an important environmental impact. It was discovered by Bekun et al. (2019) that using renewable energy slows down environmental deterioration. This is supported by (Wang and Dong 2019), who show how renewable energy use and ecological footprint in sub-Saharan African nations are related.

$$\frac{\partial \mathrm{EF}_{it}}{\partial \mathrm{RE}_{it}} => 0$$

Dogan et al. (2019) demonstrated that non-renewable energy usage had a detrimental impact on ED in MINT nations, and Baloch et al. (2019) supported these conclusions.

$$\frac{\partial EF_{it}}{\partial NRE_{it}} < 0$$

The growing greenhouse gas pressure caused by the burning of nonrenewable energy sources is evidence of this. Because both companies and home consumers have favored nonrenewable energy solutions over renewable energy, even demographic shifts like urbanization and life expectancy have contributed to the degradation of the environment.

3.2 Empirical Model

The empirical model examines the role of energy sources for environment and innovation nexus. Our model illustrates how environment and innovation nexus is mediated by energy sources. In this regard we have considered two separate equation to be estimated by SUR model. However, the mediation effects (Baron and Kenny (1986)) has been calculated by Sobel test.

EF Models

1st Model

$$RE_{it} = \alpha_1 + \alpha_2 TI_{it} + u_{i,t} \quad (1)$$

$$EF_{it} = \beta_1 + \beta_2 TI_{it} + \beta_3 RE_{it} + \beta_4 Z_{it} + u_{it} \quad (2)$$

2nd Model

$$NRE_{it} = \gamma_1 + \gamma_2 TI_{it} + u_{i,t} \quad (3)$$

$$EF_{it} = \delta_1 + \delta_2 TI_{it} + \delta_3 NRE_{it} + \delta_4 Z_{it} + u_{it} \quad (4)$$

These four equations will be estimated by taking EF as the environmental indicator, and then re-estimated by replacing EF with CO2.

CO2 Models

1st Model

$$RE_{it} = \alpha_1 + \alpha_2 TI_{it} + u_{i,t} \quad (1)$$

$$CO2_{it} = \beta_1 + \beta_2 TI_{it} + \beta_3 RE_{it} + \beta_4 Z_{it} + u_{it} \quad (2)$$

2nd Model

$$NRFE_{it} = \gamma_1 + \gamma_2 TI_{it} + u_{i,t} \quad (3)$$

$$CO2_{it} = \delta_1 + \delta_2 TI_{it} + \delta_3 NRE_{it} + \delta_4 Z_{it} + u_{it} \quad (4)$$

Where i denotes the country (i=1,…, 23) and t denotes time period (t=1990 - 2022)

The above two equations represent a seemingly unrelated regression model where the dependent variable is determined by a set of different independent variables. In equation (1) renewable energy RE_{it} is the dependent variable and technological innovation (TI_{it}) is the independent variable and in equation (2) ecological footprint (EF_{it}) is dependent and non-renewable energy (NRE_{it}) and technological innovation (TI_{it}) as independent variables.

Also in equation (3) non-renewable energy (NRE_{it}) is the dependent variable technological innovation (TI_{it}) is the independent variable and in equation (4) ecological footprint (EF_{it}) is the dependent variable and nonrenewable energy (NRE_{it}) and technological innovation (TI_{it}) is independent variables. Where Z_{it} includes a set of control variables that is gross domestic product (GDP) urban population index (URB) and carbon emissions $CO_2 u_{it}$ denotes the error term.

The seemingly unrelated regression Zellner (1962) will be used to estimate the models, while Sobel's (1982) delta method will be used to identify the effects.

$$\text{Total Effect} = \text{Direct Effect} + \text{Indirect Effect}$$

The direct effects are captured with the estimated coefficients of empirical models. The estimated coefficients β_2, and δ_2 in equations 2 and 4 present the direct effect of ecological footprint on technological innovation.

To capture the indirect effect of TI on the environment of high-energy users the derivative of the above models by applying the chain rule will be taken as below.

$$\frac{\partial EF_{it}}{\partial TI_{it}} = \frac{\partial EF_{it}}{\partial RE_{it}} \times \frac{\partial RE_{it}}{\partial TI_{it}} \quad (5)$$

By substituting the values of the above derivatives from equation (1) and equation (2) we get.

$$\frac{\partial EF_{it}}{\partial TI_{it}} = \alpha_2 \beta_3 \quad (6)$$

Equation (6) consists of two coefficients from separate regressions, which gives the indirect effect of TI and renewable energy.

Additionally, in model two, we capture how technological progress affects high-energy consumers' environments. The derivative of the models above is obtained by using the chain rule, as shown below.

$$\frac{\partial EF_{it}}{\partial TI_{it}} = \frac{\partial EF_{it}}{\partial NRE_{it}} \times \frac{\partial NRE_{it}}{\partial TI_{it}} \quad (7)$$

By substituting the values of the above derivatives from Equation (3) and Equation (4) we get

$$\frac{\partial EF_{it}}{\partial TI_{it}} = \gamma_2 \delta_3 \quad (8)$$

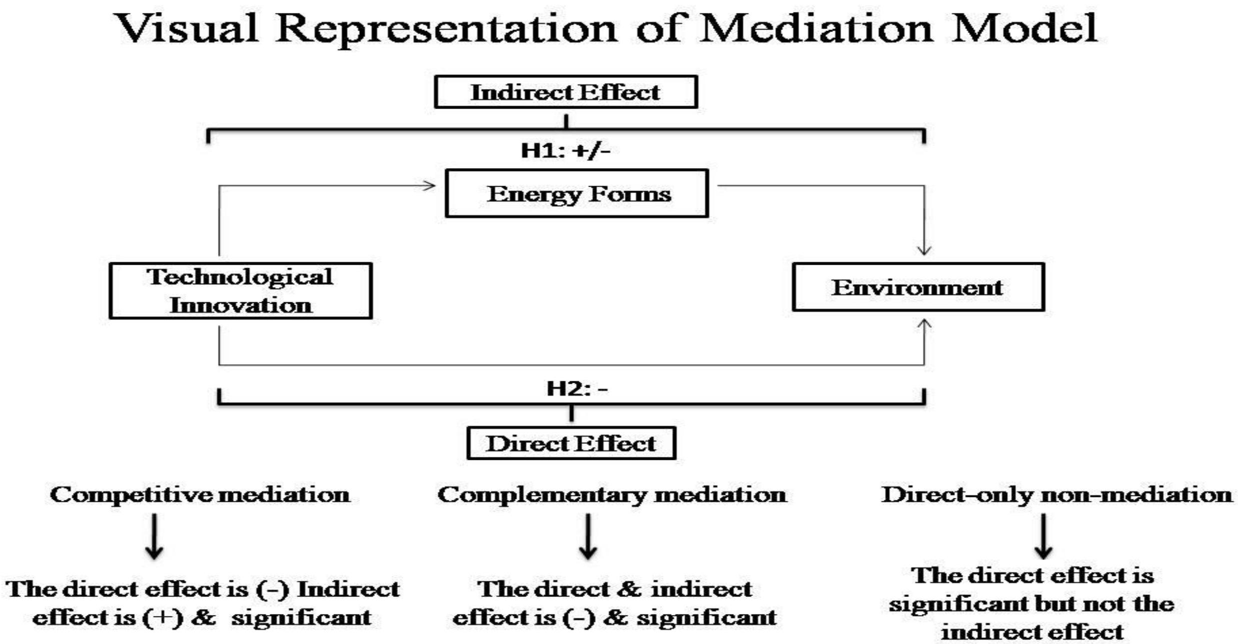
Two coefficients from different regressions make up Equation (8) which expresses the indirect impact of non-renewable energy and TI. Equations 9 and 10 can, however, be used to specify the overall impacts. Through the use of renewable energy, Equation 9 illustrates how technological advancement affects the environment. By using non-renewable energy, Equation 10 describes how technology advancement affects ecological footprints.

$$\frac{\partial EF_{it}}{\partial TI_{it}} = \beta_2 + \alpha_2 \beta_3 \quad (9)$$

$$\frac{\partial EF_{it}}{\partial TI_{it}} = \delta_2 + \gamma_2 \delta_3 \quad (10)$$

Hypotheses of the study are visualized in Figure 3.

Figure 3: Visual Representation of Mediation Model



H1: The interaction between TI and the environment is mediated, either positively/negatively, by the energy forms associated with the invention.

H2: Technological advancement has a negative direct impact on the environment in addition to the positive mediating role of energy types.

The relationship between TI and the environment is positively mediated by renewable energy, according to H1, which is the mediation effect that we first examined. This indicates that there is a favorable correlation between renewable energy and the environment, as well as between renewable energy and technical advancement.

Furthermore, the mediation effect is evident from the mediation results, which demonstrate the indirect impact of technological progress on the environment through energy forms. According to H2, technological advancement also negatively impacts the environment.

In favor of direct effect number of studies demonstrated that technological progress had a detrimental impact on the environment, with Zeraibi et al.'s major findings from 2021 suggesting that the candidate countries' declining ecological footprints are a result of TI. Additionally, Suki et al. (2022) used the bootstrapped autoregressive distributed lag (BARDL) model and observed how technological advancements led to decreased ecological footprint. Zhang et al. (2022) provide comparable findings that support the notion of adverse impacts.

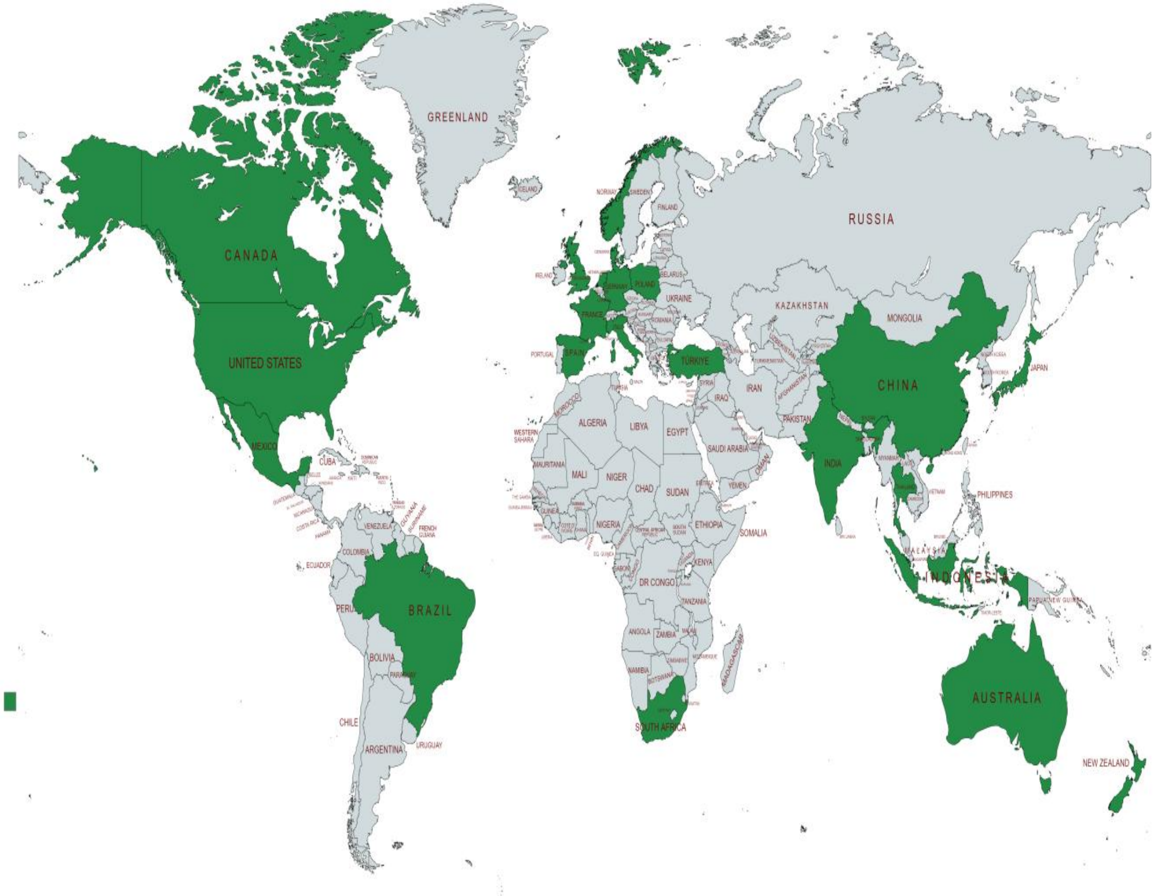
In favor of indirect effect to being considered as a substitute for traditional energy sources, renewable energy also has an important environmental impact. It was discovered by Bekun et al. (2019) that using renewable energy slows down environmental deterioration. This is supported by (Wang and Dong 2019), who show how RE use and EF in sub-Saharan African nations are related.

Dogan et al. (2019) demonstrated that non-renewable energy usage had a detrimental impact on ED in MINT nations, and Baloch et al. (2019) supported these conclusions.

3.3 Data and Variable Description

This section provides descriptions of the variables and data dimensions. The high energy using economies are the focus of analysis, while data is from 1990 to 2020. The list of countries has been derived from WDI and will comprise the economies of 23 countries with high energy consumption. Figure 4 shows the global placement of the sample under consideration. Variable descriptions and data sources are mentioned in Table 1.

Figure 4: Selected Sample Countries



Note: The green-highlighted countries on the map represent the 21[1] *high energy users included in our study.*

Table 1: Variable Description & Data Sources

Variable	Description	Variable Unit	Source
EFG_{it}	Ecological Footprint (Global Hectares)	Global Hectares	Ecological Footprint Network
EFP_{it}	Ecological Footprint (Per Person)	Per Person	

[1]These countries are Australia, Brazil, Canada, China, Denmark, France, Germany, Italy, India, Indonesia, Japan, Mexico, Netherlands, New Zealand, Norway, Poland, Spain, South Africa, Thailand, Turkey, United Kingdom, and United States.

RE_{it}	Renewable Energy	% of Total Final Energy Consumption	
NRE_{it}	Non Renewable Fossil Fuel Energy Consumption	% of Total	WDI
RD_{it}	Research and Development Expenditure	% of GDP	
EG_{it}	Economic Growth	Annual %	
$CO2_{it}$	Carbon Emission	Metric Tons Per Capita	
PT_{it}	patent application residents +patent application Non residents	Residents + non residents	

3.4 Econometric Approach

The econometric methodology followed covers the prior diagnonostics test for regression estimates and mediation effects.

Cross-sectional Dependence Test

The investigation of cross-sectional dependence (CSD) in the data can appear due three factors. These are globalization, economic block formation, and global economic interconnection. However, ignoring the presence of CSD can cast doubt on estimation results. As M. Campello et al. (2019) show, disregarding CSD might result in estimates that are skewed and ineffective. To determine whether CSD is present in the data, the CSD test statistic created by M.H. Pesran et al. (2004) has been used.

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

In order to determine whether cross-sectional dependence (CSD) exists in the data, Equation (3) provides the pairwise correlation denoted by $\widehat{\rho_{ij}}$ estimated by OLS. For this test, independence across cross-sections is assumed by the null hypothesis. Economic heterogeneity, which results from variations in economic structures, may cause this assumption to be broken, though. The test created by Yamagata and Pesaran (2008) will be used to take potential slope heterogeneity into consideration. The following equations are used in this test to account for slope heterogeneity:

$$\widetilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}(\frac{1}{N}\tilde{S} - k)$$

$$\widetilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}(\frac{1}{N}\tilde{S} - k)$$

The $\widetilde{\Delta}_{SH}$ and $\widetilde{\Delta}_{ASH}$ represent delta and adjusted delta tilde, respectively. The $\widetilde{\Delta}_{SH}$ follows the assumption of $(N, T) \xrightarrow{j} \infty$ so that $\sqrt{N}/_{T^2} \rightarrow 0$ further if the panel regression model is an I(1) (first-order autoregressive model), then $(N, T) \xrightarrow{j} \infty$ and $N/_{T} \rightarrow k$ so $\widetilde{\Delta}_{SH}$ is expressed as $\widetilde{\Delta}_{ASH}$ above.

Unit Root Test

The stationarity of the series is determined by using the tests created by Shin et al. (2003) and Perron & Perron (1988). The selected test carries additional benefits of incorporating panel heterogeneity; the Shin et al. (2003) test is especially well-suited for our investigation. This exam makes use of the following equation.

$$t - bar = (t_\theta - k_t)\sqrt{NV_t}$$

3.5 Empirical Estimates

For the estimates the seemingly unrelated equations model established by Zellner (1962) has been used. It allows for cross-sectional dependency, which is necessary to meet the goal of finding the route of transmission of ecological footprint to technological progress. Because disturbances across equations specific to each country are correlated. The system of linear equations (which may have distinct sets of explanatory variables) is estimated using a model of seemingly unrelated equations that also takes the error term's cross-equation correlation into account. The term seemingly related is sometimes considered more appropriate since the error terms are assumed to be correlated across the equations. However, the system is named seemingly unrelated because each equation is a valid linear regression on its own and can be estimated separately. Though some authors argue that the term seemingly related would be more appropriate since the error terms are assumed to be correlated across the equations, the system is named seemingly unrelated because each equation is a valid linear regression on its own and can be estimated separately. The use of Seemingly Unrelated Regression is more appropriate for obtaining the estimates due to nature of the empirical model. Further considering the energy role in environment and technology estimates the using SUR will provide efficient estimates as compared to contemporary models.

Assuming the data span T times for each cross-section unit:

Examine the following set of equations:

$y_i = X_i\beta_i + \varepsilon_i$ i=1,2…….M

Where the i-th equation in the system under consideration is indicated by the index i.

In the matrix form

$$\begin{matrix} y_1 \\ \vdots \\ y_M \end{matrix} = \begin{bmatrix} X_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & X_M \end{bmatrix} \begin{matrix} \beta_1 \\ \vdots \\ \beta_M \end{matrix} + \begin{matrix} \varepsilon_1 \\ \vdots \\ \varepsilon_M \end{matrix}$$

In thei-th equation, Ki parameters are estimated. It yields the total number of coefficients$= \sum_{i=1}^{m} K_i$. In addition $K_i > T_i$

Strictly heterogeneity is assumed, i.e.,$E(\varepsilon|X_1, \ldots, X_m) = 0$

In the SUR framework, it is possible to assume that the covariance matrix of the error term is not diagonal.

$$\Omega = E\langle \varepsilon\varepsilon | X_1, \ldots, X_m \rangle = \begin{bmatrix} \sigma_{11}^2 I & \cdots & \sigma_{1m}^2 I \\ \vdots & \ddots & \vdots \\ \sigma_{m1}^2 I & \cdots & \sigma_{mm}^2 I \end{bmatrix}$$

The system of equations can be estimated using FGLS (feasible generalized least squares) given the structure of the variance-covariance matrix of the error term.

The following phases are typically included in the two-step estimating process.
1. To get reliable and impartial estimates of the variance-covariance matrix of the error component, the OLS regression for the system of equations under consideration should be run.
2. The variance-covariance matrix of the error term estimates can be used to apply a typical GLS estimator:

$$\hat{\beta}^{SUR} = (\grave{X}\acute{\hat{\Omega}}^{-1}X)^{-1}\grave{X}\acute{\hat{\Omega}}^{-1}y$$

The OLS estimator will be near to β^SUR if the error term's variance-covariance matrix is diagonal. The SUR can be used to take into consideration any possible variability in the slopes when dealing with long and narrow panel data.

Suppose we have two panels, one long (T) and the other narrow (N) not very huge. The standard linear model can therefore be represented by the following set of equations:

$$y_1 = \acute{\beta}_1 X_1 + \varepsilon_1$$

$$y_2 = \acute{\beta}_2 X_2 + \varepsilon_2$$

$$\vdots = \vdots$$

$$y_N = \acute{\beta}_N X_N + \varepsilon_N$$

where the structural parameters' unique particular vector is represented by (β) ʁ_N.
Cross-equation correlation is taken into consideration by the SUR approach. Cross-sectional dependence is the same as this correlation in the example above. Slope heterogeneity can be tested. The homogeneity of all slopes hypothesis, H_0: β_1=⋯=β_N, can be tested using the conventional Wald test, where β_i denotes the vector of parameters for the i-th unit. A homogeneous slope can be found at 〖H〗_0: β_(1,j)=⋯=β_(N,j), where is the j-th parameter for an i-th unit.

Taking cross-equation dependence into account, the SUR technique yields estimates that are more efficient. The LM statistic (Breusch and Pagan, 1983) can be used to test for cross-equation dependence.

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{i,j}^2$$

The cross-sectional correlation coefficient is denoted by$\hat{\rho}_{i,j}^2$.

$$\hat{\rho}_{i,j} = \frac{\sum_{t=1}^{T} \hat{\varepsilon}_{it}\hat{\varepsilon}_{jt}}{(\sum_{t=1}^{T} \hat{\varepsilon}_{it})^{\frac{1}{2}} (\sum_{t=1}^{T} \hat{\varepsilon}_{jt})^{\frac{1}{2}}}$$

The LM statistic is asymptotically distributed as χ2 with N (N − 1)/2 degrees of freedom and is valid for fixed N as T→∞. The commands that will be analyzed are from Nguyen and Nguyen (2010).

4. Results and Discussions

4.1 Descriptive Statistics

Descriptive statistics indicate the properties of the data series used in the analysis are shown in Table 2. All series have positive mean and standard deviation, with the exception of patent applications PT_{it}, which have the highest standard deviation of any variable. There are multiple reasons for this, such as the dynamic nature of policies, the growing impact of globalization on innovation, and the swift progress of technological developments. On the other hand, the research and development expenditure, or RD_{it} has the least variation indicated by lowest standard deviation. The reason can be the long-term planning horizons that these industries' businesses have adopted, achieving efficiency gains, and the possibility of standardized government funding mechanisms for clean energy technologies. The distributional patterns of the variables are different as revealed by skewness. All variables except non-renewable energy NRE_{it} EG_{it} are positively skewed. All variables display platykurtic distributions, except EFP_{it},NRE_{it}andRD_{it}. In contrast, leptokurtic distributions are shown by EFP_{it}, NRE_{it}, and RD_{it}.

Table 2: Descriptive Statistics

variable	Mean	SD.	Min	Max	Skewness	Kurtosis
EFG_{it}	5.400	8.870	2.280	5.280	3.178	13.383
EFP_{it}	4.875	2.377	.680	10.926	.254	2.358
RE_{it}	18.881	15.698	.61	61.37	1.150	3.356
NRE_{it}	78.610	13.441	46.225	98.526	-.682	2.282
RD_{it}	1.526	.845	.0475	3.422	.310	2.118
EG_{it}	2.753	4.411	-18.674	14.230	-1.242	7.448
$CO2_{it}$	7.525	4.684	.647	20.469	.815	3.189
PT_{it}	74615.09	192786.7	837	1400661	4.620	29.276

4.2 Cross sectional Dependence

Conventional regression models function under the assumption that errors related to individual observations are independent. The error term of one observation may, however, be influenced by other observations indicating cross-sectional dependence (CSD) in real-world data. The dependency among groups, if left untreated may lead to biased analysis. Therefore, to check cross sectional dependence the Pesaran (2004) CSD test has been used. This will guarantee our results' robustness and improve the validity of the inferences made from the analysis. Table 3 presents the findings from the CSD test (Pesaran, 2004). The CSD test results show that the null hypothesis is rejected. Cross-section dependence appears to exist based on the significance of the null hypothesis.

Table 3: Cross-Sectional Dependence Test

Variables	CD	CSD	Correlation	Abs. Corr.
EFG_{it}	21.33***	21.331***	0.244	0.497
EFP_{it}	16.46***	16.461***	0.189	0.559
RE_{it}	11.11***	11.109***	0.132	0.583
$NRFE_{it}$	1.75*	1.754*	0.022	0.553
RD_{it}	28.94***	28.941***	0.429	0.579
EG_{it}	33.54***	33.535***	0.385	0.388
$CO2_{it}$	13.72***	13.718***	0.162	0.546
PT_{it}	35.50***	35.501***	0.407	0.493

4.3 Heterogeneity Test

Table 4 displays the results of the heterogeneity test using both RE and NRE. The null hypothesis (H_0) of homogenous slope coefficients is tested by observations reported by Pesaran and Yamagata (2008). Their findings demonstrate that the slope coefficients exhibit statistically significant heterogeneity.

Table 4: Slope Heterogeneity Test (Ho: slope coefficients are homogenous)

	RE_{it}

	$\widetilde{\Delta}RE_{it}$	Decision
$\widetilde{\Delta}$ $\widetilde{\Delta}_{adusted}$	332*** 425***	Slope coefficients are heterogeneous
$\widetilde{\Delta}$ $\widetilde{\Delta}_{adusted}$	997*** 1.28***	
$\widetilde{\Delta}$ $\widetilde{\Delta}_{adusted}$	389*** 498***	
	$NRFE_{it}$	
$\widetilde{\Delta}$ $\widetilde{\Delta}_{adusted}$	385*** 493***	Slope coefficients are heterogeneous
$\widetilde{\Delta}$ $\widetilde{\Delta}_{adusted}$	497*** 636***	
$\widetilde{\Delta}$ $\widetilde{\Delta}_{adusted}$	813*** 1.04***	

4.4 Unit roots Results

To discuss the stationarity properties of the used series, table 5 has been segregated into two panels. The 1st panel report the unit root results (Im et al., 2003) test while 2nd panel exhibit the stationarity properties by PP- Fisher Chi-square. The findings show that all variables are stationary at the first difference, with the exception of economic growth EG_{it}. The results in the second panel also show the degree of stationary that is present in the analytical series used. With the exception of EG_{it}, EFG_{it}, and EFP_{IT}, all other variables show stationary at the first difference.

Table 5: Unit Root Test (Im, Pesaran and Shin)

Variables	Level	Difference	Decision
EFG_{it}	-2.511	-4.436***	I(1)
EFP_{it}	-2.494	-4.413***	I(1)
RE_{it}	-2.055	-3.612***	I(1)
NRE_{it}	-2.529	-3.503***	I(1)
RD_{it}	-1.780	-2.667*	I(1)
EG_{it}	-3.257***	-	I(0)
$CO2_{it}$	-2.205	-3.424***	I(1)
PT_{it}	-2.069	-3.666***	I(1)

PP - Fisher Chi-square			
Variables	Level	Difference	Decision
EFG	-3.148***	-	I(0)
EFP_{it}	-3.122***	-	I(0)
RE_{it}	-2.222	-4.826***	I(1)
NRE_{it}	-2.517	-4.619***	I(1)
RD_{it}	-1.868	-3.858***	I(1)
EG_{it}	-3.787***	-	I(0)
$CO2_{it}$	-2.375	-5.061***	I(1)
PT_{it}	-2.137	-5.013***	I(1)

4.5 Estimation Results

Two proxies of TI have accomplished the estimation. Table 6 reports the SUR estimates of equation 1 and equation 2 by using two proxies for capturing its effect on the environment. While column 1 and column 2 provide estimates by using ecological footprint, and column 3 and column 4 provide the estimates of the models by using emission levels. Patent application resident and nonresident are combined to provide the proxy of TI, represented as (pt).

Table 6: Estimates from SUR for Renewable Energy as Mediator

Variables	$LEFP_{it}$		$LCO2_{it}$	
	Eq.1	Eq.2	Eq.1	Eq.2
Dep. Variables	RE_{it}	$LEFP_{it}$	RE_{it}	$LCO2_{it}$
PT_{it}	-.1738*** (.0296)	.0023 (.0018)	-.0173*** (.0029)	.0084*** (.0021)
RE_{it}	-	-.0238*** (.0026)	-	-.0253*** (.0029)
NRE_{it}	-.9436*** (.0277)	-.0072* (.0029)	-.9436*** (.0277)	.0048 (.0033)
EG_{it}	1.2578*** (.0903)	-.0156* (.0064)	1.2578*** (.0903)	-.0067 (.0072)
Cons	89.8527*** (2.1792)	2.4876*** (.2700)	89.8527*** (2.1792)	1.8553*** (.3035)
No. Obs	564	564	564	564
R_1^2	0.7098	-	0.7098	-

R_2^2	-	0.2824	-	0.4092
chi2(1)	3.902	-	1.391	-
Pr	0.0482	-	0.2382	-

Equation 1 shows that adopting renewable energy (RE) and patent applications (PT1) are negatively and statistically significantly correlated. According to the estimated coefficient, there is a 0.17% decrease in RE_{it} for every 1% rise in PT_{it}. The result of the analysis is in line with Alam and Murad (2020) who argued for same results for OECD economies. In the current case, the significant negative impact of TIs on RE is because the initial innovations are not directed towards the renewable energy sector. They still consume an enormous amount of fossil energy like oil and gas to make clean energy technologies.

The coefficient of non-renewable energy NRE_{it} to adoption of renewable energy RE_{it} is statistically significant negative. This negative association suggests interesting empirics related to both sources of energy. It suggests that a decline in RE_{it} adoption is linked to a larger reliance on NRES. The magnitude of 0.9438% indicates that for every 1% increase in NRE_{it} expected to cause decline RE_{it} by 0.9438%. The justification is that exploiting already-existing, established NRES may lead to path dependence. The infrastructure and investments primarily focused on NRE_{it} can cause inertia and impede the creation and uptake of alternative RE_{it} solutions. Recent research by Steffen et al. (2020) supports this concept, highlighting the "inertia of energy demand" where existing infrastructure and user habits can make it difficult to shift towards renewable energy.

In contrast, there is a positive and statistically significant correlation between economic growth EG_{it} and RE_{it}. This suggests that there is a positive correlation between economic expansion and a rise in re-adoption. Additionally, the results show that a 1.25% increase in RE_{it} is correlated with a 1% increase in EG_{it}. Growth in the economy may raise disposable income, which may increase demand for greener energy sources and ecologically friendly technology like renewable energy. The outcome is consistent with Payne (2011) for the US economy, Leitao (2014) for the Portuguese economy, and Khoshnevis Yazdi and Shakouri (2017) for Germany.

Equation 2 reports the estimates of technology, renewable, non-renewable and economic growth on the environment. The TI (PT_{it}) indicate a positive effect on the environment. However, the magnitude is 0.23% in EFP_{it} and 0.8426% in$CO2_{it}$. These results are contradictory with research by Chen et al. (2022), Raihan et al. (2022), and Haldar and Sethi (2022), who indicated that TI has a beneficial impact on environment in emerging economies. Technological developments might strive to increase efficiency that play a role to effect environment positively.

In contrast, with both EFP_{it} and $CO2_{it}$ emissions, RE_{it} shows a statistically significant negative coefficient. This suggests a favorable impact of RE adoption toward the environment. As the coefficient indicates more renewable energy consumption will result in a reduction in CO2 emissions. This idea is further supported by the magnitude, which shows that 1 unit rise in RE_{it} causes a 2.37% drop in EFP_{it} and .0253 in $CO2_{it}$ emissions respectively. These results are consistent with the idea that renewable energy may significantly reduce the EFP_{it} (Sun et al., 2023; Saqib and Usman, 2023; Wang et al., 2023). The adoption of RE causes a 25.346% drops in $CO2_{it}$ emission. This result is in line with the studies of Kirikkaleli and Adebayo (2020) for the global economy and Miao et al. (2022) for NICs (Newly Industrialized Countries); these studies show a negative correlation between the use of renewable energy sources and environmental deterioration.

The coefficient of $NRFE_{it}$ in Eq2 is negative when it comes to EFP_{it}, but positive when it comes to $CO2_{it}$ emissions. The magnitude of the effect is 0.726% and 0.676% for both respectively. However, it can be argued that region's high population density and rapid economic expansion have raised energy demand, which has mostly been satisfied by burning fossil fuels. Fossil fuel consumption, however, has led to greenhouse gas emissions and air pollution, which worsen the environment and promote climate change. Therefore, the demand effect overcomes the supply effect in case of former. This findings are supported by Imamoglu (2018).

Fossil fuels can be replaced with sustainable energy sources such as hydro, wind, solar, and biomass (Usman et al., 2022). The fossil fuel burning increases the emission level of high energy using economies and these results are consistent with the findings of (Dogan et al., 2019), which show that non-renewable energy use has a positive effect on ED in MINT nations. (Baloch et al., 2019) found the same thing, but for BRI countries.

The economic growth (EG) effects the environment negatively while the estimate is 1.562% and 0.6765% for EFP_{it} and $CO2_{it}$ respectively. The EG_{it} Exhibits a negative and statistically significant effect. However, it can be argued based on the estimated coefficient that initial growth level are least concerned about environment. Similar findings were found in Arouse et al.'s research (2022) on the factors influencing emissions for the BRICS countries using panel quantile regression from 1990 to 2018. Similar to the findings of Gyamfi et al. (2022) for Sub-Saharan countries and Miao et al. (2022) for BRICS economies, this result is also consistent.

The constant term is significanct for both $EFP_{it}$and $CO2_{it}$ in both Eq1 and Eq2.

Table 7: Estimates from SUR for Non- Renewable Energy as Mediator

Variables	$LEFP_{it}$		$LCO2_{it}$	
	Eq.1	Eq.2	Eq.1	Eq.2
Dep. Variables	NRE_{it}	$LEFP_{it}$	NRE_{it}	$LCO2_{it}$
PT_{it}	-.0693** (.0263)	.0023 (.0018)	-.0693** (.0263)	.0084*** (.0021)
RE_{it}	-.7119*** (.0209)	-.0230*** (.0026)	-.7119*** (.0209)	-.0253*** (.0029)
NRE_{it}	-	-.0072* (.0029)	-	.0048 (.0033)
EG_{it}	1.0181*** (.0802)	-.0156* (.0064)	1.0181*** (.0802)	-.0067 (.0072)
Cons	89.0829*** (.5589)	2.4876*** (.2700)	89.0829*** (.5589)	1.8553*** (.3035)
No. Obs	564	564	564	564
R_1^2	0.6842	-	0.6842	-
R_2^2	-	0.2824	-	0.4092
chi2(1)	46.297	-	44.469	-
Pr	0.0000	-	0.0000	-

The estimation results of the SUR model, with Non-Renewable Energy as the mediator, are reported in Table 7. Non-renewable energy NRE_{it} shows a statistically significant negative coefficient with patent applications PT_{it} in Eq 1. Further evidence from the data shows that a 1% increase in PT_{it} corresponds to a

0.0693% drop in NRE_{it}. This implies an inverse relationship, meaning that there is a corresponding increase in PT_{it} activity as a result of NRE_{it} declines. This conclusion implies that as reliance on conventional energy sources declines, there may be a shift towards innovation.

Additionally, the renewable energy source shows a statistically significant negative coefficient with NRE_{it}. The data suggests a negative correlation between the increase in RE_{it} use and the decrease in $NRFE_{it}$ consumption. The findings corroborate this idea, showing that a 1% increase in RE_{it} corresponds to a 0.7119% reduction in NRE_{it}. When renewable energy (RE) is used more frequently, it becomes a more appealing and maybe less expensive option than NRE. Due to a price effect (where customers choose the less expensive option) and a substitution effect, this may result in a decrease in NRE_{it} consumption. This pattern implies that the development of RE_{it} can help create a future in energy that is both possibly affordable and more sustainable. This is consistent with research by Gernot and Richard (2012), who investigated how consumer behaviors are impacted by the adoption of renewable energy sources, hence influencing the use of NRES.

In contrast, there is a statistically significant positive correlation between economic growth EG_{it} and NRE_{it}. These results also show that an increase of 1% in EG_{it} corresponds to a 1.018% increase in NRE_{it}. It would appear that this energy source has played a significant role in developing economies, as evidenced by the suggestion that the consumption of non-renewable energy has supported economic progress. Energy sources such as NRE_{it} are widely accessible and reliable for economic growth. This is because the infrastructure for transportation and use of these fuels is well-developed and they are frequently less expensive to obtain. Consequently, when economies grow, so do their energy needs, which raises $NRFE_{it}$ consumption to satisfy those needs. Our results on the impact of non-renewable energy use on economic growth are consistent with some previous research (Apergis and Payne, 2011; Bhattacharya et al., 2016; Zafar et al., 2020; Shahbaz et al., 2020).

In Equation 2, the emissions of EFP_{it} and $CO2_{it}$ show statistically significant and positive coefficients with PT_{it}. This shows a positive correlation, indicating that stronger environmental stressors are linked to increased PT_{it} activity. The hypothesis is further supported by the data, which show that a 1 unit rises in PT_{it} corresponds to an increase in $CO2_{it}$ emissions of 0.8426%. These results align with research conducted by Haldar and Sethi (2022) and Raihan et al. (2022), which noted that TI has a beneficial impact on ED in developing nations. Technological developments might strive to increase efficiency, but they might also have unforeseen negative effects on the environment.

On the other hand, with regard to both EFP_{it} and $CO2_{it}$ emissions, RE_{it} shows a statistically significant negative coefficient. The findings substantiate this idea, showing that a rise of 1 unit in RE_{it} corresponds to a reduction of 2.076% in EFP_{it} and 2.534% in $CO2_{it}$ emissions. This result aligns with the studies of Kirikkaleli and Adebayo (2020) about the global economy and Miao et al. (2022) regarding NICs; yet, it is at odds with the research conducted by Alola et al. (2021) regarding China and Akadiri et al. (2022) regarding China. These studies show a negative correlation between the use of renewable energy sources and environmental deterioration.

In Eq2, NRE_{it} denotes a positive coefficient with CO2 emissions but a negative coefficient with EFP_{it}. The negative coefficient implies that there might be a correlation between a rise in $Nrfe_{it}$ adoption and a fall in EFP_{it}. The results show that a 1 unit raises in $Nrfe_{it}$ causes a 0.726% drop in EFP_{it}, even though the total influence on environmental pressures may be complex. Our findings are in line with those of (Dogan et al., 2019), who found that non-renewable energy use had a beneficial impact on ED in MINT nations. (Baloch et al., 2019) found the same thing, but for BRI countries.

The correlation between EG_{it} and EFP_{it} in Eq2 is negative, suggesting that EFP_{it} may decline as economic growth increases. According to the data, there is a 1.562% drop in EFP_{it} for every unit rise in EG_{it}. Economic growth is frequently linked to heightened environmental constraints. Similar findings were found in Awosusi et al.'s research (2022) on the factors influencing emissions for the BRICS countries using panel quantile regression from 1990 to 2018. Similar to the findings of Gyamfi et al. (2022) for Sub-Saharan countries and Miao et al. (2022) for BRICS economies, this result is also consistent. The constant term is significant for both EFP_{it} and $CO2_{it}$ in both Eq1 and Eq2.

Mediation Effects

The estimated coefficients of the direct, indirect, and mediation effects are shown in Table 8. The first two panels report both RE_{it} and NRE using TI as a proxy represented by resident and non-resident patent applications. The final two panels report the effects of using research and development (R&D) spending as a proxy for TI.

Table 8: Mediation Effects for both Mediators

		RE (PT)		
	Direct	Indirect	Total	Mediation
LEFG	-.0173874***	.0004415***	.0053176***	.0909943***
	(.0029639)	(.0001077)	(.0003209)	(.0239533)
LEFP	-.173874***	.0040117***	.0063605**	1.711991
	(.0296385)	(.0008202)	(.0019564)	(1.461085)
LCO2	-.0173874***	.0004407***	.0088674***	.0527401**
	(.0029639)	(.0000907)	(.0021119)	(.0181624)
		NRE (PT)		
LEFG	-.0693038**	.0016948*	.0504559***	.0364528*
	(.0263566)	(.0007352)	(.0032578)	.0160965
LEFP	-.0693038**	.0005033*	.0028521	.2147944
	(.0263566)	(.0002825)	(.0018864)	(.2181054)
LCO2	-.0693038**	-.0003367	.00809***	-.040294
	(.0263566)	(.0002663)	(.0021132)	(.0324854)
		RE (RD)		
LEFG	-3.501346***	.162177***	.2959412***	1.374586*
	(.5259521)	(.0335309)	(.0720631)	(.7640757)
LEFP	-3.501346***	.030931**	.4284451***	.1087421**
	(.5259521)	(.0104417)	(.0279148)	(.0387335)
LCO2	-3.501346***	.0356231**	.5385002***	.1064617**
	(.5259521)	(.0112883)	(.0297428)	(.0352169)
		NRE (RD)		
LEFG	-2.347251***	.0921879***	.2259521**	.7813703*

	(.4721066)	(.0255753)	(.0718608)	(.4585635)
LEFP	-2.347251***	-.0076068	.3899073***	-.0267428
	(.4721066)	(.0073111)	(.0282191)	(.0254029)
LCO2	-2.347251***	-.0329438**	.4699333***	-.0984544**
	(.4721066)	(.0100822)	(.0306749)	(.0296501)

All three environmental indicators have significant, negative direct effects of RE_{it}, suggesting that RE_{it} helps to reduce these environmental burdens. While the indirect effects are positive and statistically significant. This implies that PT_{it} causes environmental pressures to rise due to rising RE_{it} adoption. It's interesting that RE_{it} had favorable and statistically significant overall effects considering all three environmental indicators.

Considering the 2nd mediator non-renewable energy NRE_{it} effects as a possible link between pt and the environmental indicators $CO2_{it}$, EFG_{it}, and EFP_{it}. The direct effect is negative and significant. This suggests that using NRE_{it} lessens the load on the environment. However, the indirect impacts of NRE_{it} on the environmental indicators were statistically significant and positive for EFG_{it} and EFP_{it} but not for $CO2_{it}$ emissions.

4.7 Discussion

The presence of negative direct and positive indirect effects implies competitive mediation (suppressive mediation). An important and diametrically opposed set of direct and indirect effects characterize competitive mediation (suppressive mediation). In this instance, the positive indirect effect mediated by RE_{it} balances the negative direct effect of PT_{it} on environmental indicators. This is consistent with research by Hair et al. (2014), who hypothesize that competitive mediation may occur when an independent variable affects the dependent variable positively and negatively via several pathways.

The suppressive mediation arises when there are two compensatory pathways, these happen in any system that necessities to maintain stability. It can be well explained with help of an example if x variable has effect on y. while increase in x decreases y further if a m(mediator) has a negative effect on y . However, it is explained that x has direct effect on y. while there is compensatory pathway involving M effecting y to offset changes in y happened due to X. same situation is happening in our case. The opposing signs of both effects indicate a complex relation between dependent and independent variables. It indicates that the independent variable decrease the dependant directly while it increases it through the mediator.

In the case of non-renewable energy sources, the presence of both a direct and indirect negative impact on the environment suggests complementary mediation. Complementary mediation occurs when both direct and indirect effects are negative and statistically significant. This is consistent with research by Hair et al. (2014), who hypothesize that complementary mediation may occur when an independent variable negatively affects the dependent variable.

It helps to understand the complex mechanism of TI effecting the environment. It has enhanced the importance of energy forms and explains that the effect is not straight forward. This is consistent with the findings of Hair et al. (2014), who highlight the possibility of competing mediation when the independent variable affects the dependent variable in both positive and negative ways via several pathways. Our research indicates that CO2 emissions do not directly impact the environment, independent of other factors. This implies that mediation plays an important role. In summary, when the direct effect is negative, and the indirect effect is positive, it implies a complex relationship where the IV simultaneously exerts opposing influences on the DV through different pathways. This calls for a deeper understanding of the mediator's role and potentially different strategies to optimize outcomes.

Robustness check

To check the robustness of the estimated results, we replaced the R&D variable instead of the Patent. Moreover, EFG is used instead of EF in all the estimated equations. The results are reported in Tables 9a-9c. The findings confirm that the variables have the same sign and significance. Although, there is some change in magnitude. These changes confirms the reliability and robustness of the estimated results.

Table 9a: RD (RE)

Variables	LEFP		LCO2	
	Eq.1	Eq.2	Eq.1	Eq.2
Dep. Variables	RE	LEFP	RE	LCO2
RD_{it}	-3.5013*** (.5259)	.3975*** (.0290)	-3.5013*** (.5259)	.5028*** (.0308)
RE_{it}	-	-.0088** (.0026)	-	-.0101*** (.0028)
$NRFE_{it}$	-.9271*** (.0338)	.0032 (.0030)	-.9271*** (.0338)	.0140*** (.0032)
EG_{it}	1.2408*** (.1076)	-.0066 (.0065)	1.2408*** (.1076)	.0095 (.0069)
CONS	92.2321*** (2.7887)	.8230** (.2863)	92.2321*** (2.7887)	.1443 (.3043)
No. Obs	384	384	384	384
R_1^2	0.6901	-	0.6901	-
R_2^2	-	0.4721	-	0.5793
chi2(1)	0.746	-	11.842	-
Pr	0.3877	-	0.0006	-

Table 9b: NRE (RD)

Variables	LEFP		LCO2	
	Eq.1	Eq.2	Eq.1	Eq.2
Dep. Variables	NRE	LEFP	NRE	LCO2
RD_{it}	-2.3472*** (.4721)	.3975*** (.0290)	-2.3472*** (.4721)	.5028*** (.0308)
RE_{it}	-.7128*** (.0260)	-.0088** (.0026)	-.7128*** (.0260)	-.0101*** (.0028)

NRE_{it}	-	.00324 (.0030)	-	.0140*** (.0032)
EG_{it}	1.1628*** (.0920)	-.0066 (.0065)	1.1628*** (.0920)	.00956 (.0069)
CONS	91.7786*** (1.0373)	.8230** (.2863)	91.7786*** (1.0373)	.1443 (.3043)
No. Obs	384	384	384	384
R_1^2	0.6844	-	0.6844	-
R_2^2	-	0.4721	-	0.5793
chi2(1)	7.031	-	8.215	-
Pr	0.0080	-	0.0042	-

Table 9c: (EFG)

RE (PT)			NRE (PT)	
Variables	LEFG		LEFG	
	Eq.1	Eq2	Eq.1	Eq2
PT_{it}	-.0173874*** (.0029639)	.0048761*** (.0003213)	-	-
PT_{it}	-	-	-.0693038** (.0263566)	.048761*** (.0032129)
RE_{it}	-	-.0253945*** (.0044314)	-.7119701*** (.0209505)	-.0253945*** (.0044314)
$NRFE_{it}$	-.943689*** (.0277691)	-.0244552*** (.0051018)	-	-.0244552*** (.0051018)
EG_{it}	1.257816*** (.0903543)	.074775*** (.0110221)	1.01813*** (.0802353)	.074775*** (.0110221)
Cons	89.85273*** (2.179284)	21.24092*** (.4595004)	89.08293*** (.5589409)	21.24092*** (.4595004)
No. Obs	564	564	564	564
R_1^2	0.7098	-	0.6842	-

R_2^2	-	0.3853	-	0.3853
chi2(1)	14.834	-	20.850	-
Pr	0.0001	-	0.0000	-
RD (RE)			RD (NRE)	
RD_{it}	-3.501346*** (.5259521)	.1337642* (.0716272)	-2.347251*** (.4721066)	.1337642* (.0716272)
RE_{it}	-	-.0463185*** (.0065803)	-.7128591*** (.0260554)	-.0463185*** (.0065803)
$NRFE_{it}$	-.9271643*** (.0338884)	-.0392748*** (.0075046)	-	-.0392748*** (.0075046)
EG_{it}	1.240858*** (.1076484)	.1251632*** (.0161045)	1.162838*** (.0920394)	.1251632*** (.0161045)
Cons	92.23214*** (2.788701)	22.81061*** (.7054516)	91.77868*** (1.037374)	22.81061*** (.7054516)
No. Obs	384	384	384	384
R_1^2	0.6901	-	0.6844	-
R_2^2	-	0.1842	-	0.1842
chi2(1)	16.897	-	29.005	-
Pr	0.0000	-	0.0000	-

5. Conclusion and Policy Implications

Environmental degradation has derived the research on the relationship between energy consumption and technological innovation. However, energy use can place more burden on the environment. Therefore, the role of energy is crucial in nexus of innovation to environment. For this purpose by utilizing a sample of 23 economies with notable energy consumption between 1990 and 2020, the study applies a sophisticated econometric technique to investigate the connection between EF and technological progress. The seemingly unrelated regression (SUR) model is employed to account for potential cross-sectional dependence and slope heterogeneity. The research explains the complex connections that exist between environmental indicators, energy sources (RE and NRES), and TI. The findings of the analysis provide evidence that an increase in TI declines both forms of energy. Further, the higher use of renewable energy has a favorable effect on the environment. While the NREC increases the emission levels of the high energy using economies. However, in the case of EF, the demand side is more pronounced for depicting the positive impact on the environment. The result of the mediation analysis portrays the competitive (suppressive) mediation. The presence of the suppressive mediation is an evidence that handling innovation and environment nexus should not ignore the energy sources. The ignorance of the energy sources in the explored nexus will lead to spurious results.

Policymakers need to understand that TI has two distinct effects on the environment. In addition to supporting for the use of renewable energy, it is critical to ensure that related technology developments support sustainability objectives. When making strategic choices, firms and investors should consider the combined consequences of adopting RES and technology advancement. To optimize the advantages for the environment, investments in renewable energy projects should be supplemented with initiatives to advance TI. The mediation analysis has implications on multiple dimensions. The indication of opposing signs of direct and indirect effect proposes complex pathways and associations. This type of mediation suggest to incorporate th energy forms while dealing with environment and innovation nexus. Skipping the energy form can lead to misspecification of the nexus. However, in the practical arena, this proposes that handling the mediator can enhance its positive effects. Further, the mediator analysis enhances the understanding of the mechanism involved in the effect of exogenous factors on endogenous variables. Recognizing the consequences of competitive mediation highlights the significance of comprehensive strategies for sustainable development. For environmental sustainability to be achieved over the long term, both the positive and negative effects of energy choices and technological improvements must be balanced.

Further investigation into the mechanisms underlying competitive mediation and how various characteristics and situations may affect these interactions are two potential areas of future research.

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