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Article

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Assessing the Connection between Nuclear and Renewable Energy on Ecological Footprint within the EKC Framework: Implications for Sustainable Policy in Leading Nuclear Energy-producing Countries

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ABSTRACT

Numerous Sustainable Development Goals (SDGs) set by the United Nations can't be completed without switching to alternative energy sources. Countries need to find common ground between energy security, affordability, accessibility, and environmental sustainability if they are to lay the groundwork for competition and success. Considering the connection between economic growth, nuclear power generation, renewable energy consumption, and non-renewable energy usage, this study examines the ecological footprints of leading nuclear energy-producing countries (the United States, France, China, Russia, Japan, South Korea, Canada, the Ukraine, the United Kingdom, and Germany) from 1990 to 2020. In order to perform such a thorough empirical investigation, this study makes use of advanced econometric methods. According to the long-term cointegration study, environmental quality is negatively impacted by economic growth and the use of non-renewable energy, while it is positively impacted by the square of economic growth, the use of nuclear energy, and the use of renewable energy. The study found that the ecological footprint is directly correlated with both nuclear power and economic growth. Meanwhile, both renewable and non-renewable energy sources were found to have an effect on the ecological footprint in a causal manner. The findings of this study emphasize the significance of the world's major nuclear energy producing countries harmonizing their energy policies and developing a common energy strategy that includes equitable distribution of key components of the global nuclear energy sector.

Keywords: Economic Growth, Renewable Energy, Nuclear Energy, Ecological Sustainability, EKC
JEL Classifications: C24, O13, Q43

1. INTRODUCTION

Deterioration of the environment and its consequences for biodiversity and human health continue to be at the forefront of international policy debates and the key focus of the world agenda. The concept of sustainable development relies on the trinity of economic, social, and ecological well-being. These bases are now absolutely necessary to guarantee human survival. The ecosystem, water supplies, infrastructure, food production, and human health are all negatively impacted by extreme weather events. With the speed at which environmental conditions are shifting and the state of the ecosystem deteriorating, environmental sustainability has risen in importance as one of the three pillars of sustainable development. The ecological footprint, and more especially the carbon footprint, has come to be seen as an essential indicator of environmental deficit and environmental sustainability, and as such has gained widespread recognition as a vital measure of sustainable development. The literature on ecological footprints has taken a holistic view, including the interplay between economic, geographical, human, and social activities, among other factors, to determine the ecological systems that follow.

Constantly in the forefront of international concern is the state of the environment and its impact on human health and the environment (Azam et al., 2023). The concept of sustainable development is based on three pillars: Social, economic, and environmental sustainability, and it aims to address these problems. An increase in the frequency of extreme weather events has led to an increase in mortality and disease rates as well as disruptions to ecosystems, water supplies, infrastructure, and food production. Sustainability in the face of accelerating environmental change and worsening ecological conditions is more important than ever. Both environmental degradation and progress toward a more sustainable future can be gauged by looking at one's ecological footprint, and this is especially true when looking at one's ecological footprint.

A country's ecological footprint is assumed to grow proportionally with its income in the early stages of economic development before leveling off at higher incomes in the EKC hypothesis. Previous studies on this topic have yielded mixed results, with some studies supporting the EKC and others finding evidence of a continuous link between wealth and ecological footprint. It's common knowledge that economic status isn't the only factor in determining an individual's ecological foot print; policies and institutions also play significant roles. Understanding the EKC's effect on the environmental footprint takes a nuanced and interdisciplinary approach due to the complexity and breadth of that influence. To promote sustainable development and reduce the ecological footprint of nations, a better understanding of the connection between wealth and ecological footprint is essential.

There can be both favorable and unfavorable consequences on the environment from countries who produce nuclear energy. Nuclear power generates significantly less carbon dioxide and other greenhouse gases than conventional power plants. This can help to reduce the overall ecological footprint of energy production and consumption, especially when compared to the emissions produced by the burning of fossil fuels. In addition, many countries with nuclear energy programs have implemented strict regulations to ensure the safe and responsible disposal of nuclear waste, which can minimize the environmental impact of nuclear energy. On the negative side, the production and transportation of nuclear fuel can result in accidents or leaks, which can have significant impacts on local ecosystems and wildlife. Additionally, the disposal of nuclear waste remains a significant challenge, as it is difficult to store safely and can have long-lasting impacts on the environment. It's also worth noting that public opinion and government laws can play a big part in determining the nuclear energy industry's environmental impact. As an example, some nations have reduced or eliminated their nuclear energy programs altogether out of fear for their citizens' health and the environment, while others have expanded their reliance on nuclear power because of its low carbon footprint.

Nuclear power's use as an energy source benefits both the planet and its inhabitants. As nuclear technology has improved, it has become a viable option for providing affordable, reliable, and trustworthy electricity to both industrialized and developing countries while simultaneously mitigating the effects of carbon emissions. A total of sixty gigatons of carbon dioxide have not been released into the atmosphere due to the use of nuclear power over the previous 50 years (IEA, 2019). Over its duration of use, this energy source produces a great deal of power with very few negative environmental effects (IAEA, 2018). The effects of climate change can be mitigated with the help of nuclear power plants, which are reliable, safe, and affordable. Nuclear energy has a cheap production cost and constant, predictable prices, notwithstanding the expensive initial capital expenditures. Nuclear power reactors boosted their output by 10% in 2019, from 2563 TWh to 2657 TWh (WNP, 2020). Nuclear power has the potential to safely and sustainably replace non-renewable energy sources, making it a leader in the energy transition (Knapp and Pevec, 2018).

Over the past few years, people have started to pay more attention to the environmental impact of nuclear energy use. Following the declaration of the Paris Agreement, nuclear energy deployment has gained widespread attention. Nuclear power has been proposed as a solution to the problems of both energy insecurity and environmental deterioration (Lee et al., 2017; Ozturk, 2017). However, developing countries may not be able to afford the high capital costs and extensive infrastructure upgrades necessary for nuclear power plant construction (Mahmood et al., 2020; Goldemberg, 2009). Even while nuclear power plants cause very little direct pollution, the requirements for supporting infrastructure are quite large. Radioactive waste management, radiation exposure, the off-site consequences of nuclear accidents (IAEA, 2018), and the possibility of explosions are just a few of the many problems that plague nuclear power (Budnitz, 2016). Further, conventional energy sources are not as likely to drastically reduce environmental pollution as the adoption of nuclear energy (Gralla et al., 2017).

Over time, many different resources have contributed to meeting the energy requirement. There has been a heavy reliance on non-renewable energy sources including natural gas, oil, and coal (Saqib, 2018; Saqib, 2021). However, the continued development of the global economy and the expansion of the human population mean that these nonrenewable resources will be exhausted in the not-too-distant future. Another reason to switch to renewable energy is because depleting non-renewable resources has a major negative impact on the ecosystem (Saqib, 2022a). Solar, geothermal, biomass, hydropower, and wind energy are just some examples of renewable and alternative energy sources that can be used without depleting them because they are naturally occurring (Baloch et al., 2019, Huang et al., 2022). Cleaner energy sources are more practical to use because they are both essentially infinite and environmentally beneficial, while nonrenewable energy resources have their limits. To add to this, many see switching to renewable and alternative sources of power as an important first step in solving the energy crisis. Due to solar and wind energy's rising competitiveness, the renewable energy business has expanded rapidly in recent years (BP, 2018). One of the most active, fast expanding, and altering industries worldwide is the renewable and alternative energy sector. Because of the influence of new finance institutions, this industry is now a major contributor to economic expansion around the world. In instance, there is agreement among experts around the world that expanded use of renewable energy is necessary to combat climate change.

This research attempts to fill a knowledge vacuum by analysing the top nuclear energy-generating countries' nuclear energy production, economic growth, renewable and non-renewable energy, and ecological footprint. Long-term and causal links across countries will be estimated using a number of different approaches. The results will help legislators, environmentalists, and energy specialists make informed decisions as they develop and implement green solutions for a more sustainable future. Governments and economies can utilize the study's findings to prioritize nuclear energy investment. Section-2 will be a literature review; Section-3 will cover data sources and model specification, Section-4 will present empirical findings and interpretations; and Section-5 will offer conclusions and policy recommendations based on the study's findings.

2. REVIEW LITERATURE

Ecological footprint and GDP growth are inversely related, according to the Environmental Kuznets Curve (EKC) theory first presented by Kuznets (1955). This theory, which stresses a quadratic link between pollution and income growth, has been corroborated by several empirical research (Dinda and Coondoo, 2006). According to the EKC theory, economic growth has a significant impact on the correlation between environmental pollution and GDP growth (Doytch and Uctum, 2016; Pham et al., 2020; Saqib et al., 2022c, d). The idea states that while energy consumption and pollutants were relatively modest during the pre-industrialization era, they increased dramatically during the modernization and growth of the manufacturing sector. Deindustrialization and the subsequent transition to a services economy lead to lower pollution. It has also been noted that the correlation between energy use and carbon dioxide emissions is quadratic (Mahmood et al., 2021; Doytch and Ashraf, 2021; Saqib et al., 2023).

The EKC hypothesis posits that as a society becomes more affluent, individuals demand a higher quality of environment and the accompanying industrialization and economic output lead to increased environmental pressures. This dynamic prompt the implementation of legislative measures and technological advancements aimed at improving efficiency and reducing emissions. A commonly employed environmental quality indicator in EKC studies is the ecological footprint. Previous research supports the EKC hypothesis for high-income countries as the turning point (TP) of the inverted U-shaped EKC curve is found to be higher in these nations than in low-income nations (Pata, 2021). The study results align with the findings of several previous studies (Dong et al., 2018; Pata and Caglar, 2021; Yang et al., 2022; Saqib, 2022b) in suggesting that increased national income as a result of economic growth is likely to drive these nations towards environmental sustainability. This is particularly relevant for E-7 economies, which are mostly low-middle-income nations, as they have not yet reached a high enough level of income to reach their TP, consistent with the literature (Dinda, 2004).

The impact of nuclear energy deployment on air quality has received more attention in the research in recent years. Nuclear power's impact on the environment has been the subject of numerous studies (Baek, 2015; Ozturk, 2017). In a similar vein, researchers have looked into how much of a role nuclear energy, which is often touted as a "clean energy source," actually plays in the relationship between economic development and environmental degradation (Baek and Pride, 2014). The available research implies that nuclear power has more potential than other renewable energy sources to slow down environmental degradation in clean and green energy scenarios (Saidi and Mbarek, 2016; Dong et al., 2018; Saqib, 2022c). In contrast, Hassan et al. (2020) discovered a negative correlation between nuclear power and pollution in the BRICS countries. Ozcan and Ulucak (2021) drew a line between the IPAT theory and the Environmental Kuznets Curve (EKC) hypothesis, arriving at the conclusion that using nuclear energy helps reduce pollution and climate change. Nuclear energy has a negative effect on carbon emissions, according to study by Mahmood et al. (2020), carbon dioxide emissions and nuclear power were found to be linked in both directions, by applying ARDL and causality analyses. Sadiq et al. (2022) examined the effects of nuclear power, financial globalization, and external debt on ecological health and economic progress in the BRICS nations. Carbon emissions, human development, and nuclear energy were all found to have a mutually reinforcing relationship. The findings also indicated that while nuclear power and financial globalization contributed positively to human development, external debt did not. On the other hand, financial globalization had a detrimental influence on environmental quality, while the use of foreign loans and nuclear energy had favorable effects. Khan et al. (2022a) used the EKC framework to analyze the linear relationship between nuclear energy and other energy sources in the top three countries for carbon emissions. The findings showed that while income growth and government final expenditure had negative effects on the environment, nuclear energy and renewable energy both had beneficial effects. The results of this investigation backed up the EKC theory for these nations. Research conducted by (Baek, 2015) into the relationship between nuclear power and environmental quality in the 12 countries with the highest nuclear power output found that nuclear power had a net positive effect on ecological wellbeing. On the other hand, this research only revealed weak support for the EKC theory during the course of the investigation.

The literature implies that using renewable energy sources can help safeguard the environment, whereas using non-renewable ones can lead to a decline in ecological performance (Mahmood and Saqib, 2022; Khan et al., 2022b). This standpoint is confirmed by a number of empirical studies, including those conducted by (Saqib et al., 2022a) for the MINT nations, (Saqib et al., 2022b) for GCC countries, and (Sharif et al., 2022; Saqib et al., 2022e) for the E7 and G7 countries. (Yue et al., 2023) discovered evidence to back up this view, too, demonstrating that switching to greener energy options had a positive impact on the environment in china while switching to fossil fuels had a negative one. In order to prove that renewable and alternative energy sources might reduce pollution in Malaysia from 1971 to 2015, Bekhet and Othman (2018) employed a vector error correction model (VECM). In a similar vein, Sarkodie and Adams (2018) discovered that renewable energy sources lowered environmental deterioration in South Africa, while fossil fuels increased contamination. Using a mix of grey prediction and vector error correction model (VECM) causation techniques, was shown to be a robust, causal link between economic growth, energy use, and carbon emissions.

While most researchers agree that renewable and alternative energy sources have a positive effect on carbon emissions, a small number of studies have found the opposite. (Bulut, 2017; Bölük and Mert, 2014; Yu et al., 2022), and other studies have found that the use of both renewable and non-renewable energy sources significantly impacts environmental pollution. There is very little evidence that switching to renewable energy sources reduces pollution, as documented by Al-Mulali et al. (2015). For a sample of twenty-four Asian countries (Lu, 2017) looked into how GDP growth, carbon emissions, and investments in renewable energy are related to one another. The study found that environmental pollution has a positive effect on the use of renewable energy, while in other countries the relationship between carbon emissions and renewable energy use is either nonexistent or negative. This suggests that the use of renewable and greener energy sources rises or falls as environmental degradation does in these countries.

3. DATA AND MODEL SPECIFICATION

The purpose of this study is to investigate the relationship between nuclear energy and ecological footprints, taking into account economic growth, renewable energy, and non-renewable energy as additional factors that determine ecological footprints for leading nuclear producing countries such as, the United States, France, China, Russia, Japan, South Korea, Canada, the Ukraine, the United Kingdom, and Germany for the time period from 1990 to 2020. These countries are among the top ten countries in terms of overall nuclear energy production worldwide. The data is gathered from various sources, including Global Footprint Network (GFN), British Petroleum Statistical Review (BP), and World Development Indicators (WDI) as mentioned in Table 1.

Model: Ecological footprint = f(economic growth, square of economic growth, financial inclusion, nuclear energy, renewable energy

$$EFP_{it} = f(GDP_{it}\ , GDP^2_{it}\ , NUE_{it}\ , RNE_{it}\ , NRE_{it})$$

$$\ln(EFP_{it}) = \alpha_0 + \alpha_{1i}\ln(GDP_{it}) + \alpha_{2i}\ln(GDP^2_{it}) + \alpha_{3i}\ln(NUE_{it}) + \alpha_{4i}\ln(RNE_{it}) + \alpha_{5i}\ln(NRE_{it}) + \mu_{it}$$

The descriptive statistics of the variables analysed are shown in Table 2. The findings reveal that the ecological footprint mean value is 3.21, followed by with the minimum (1.570) and maximum (6.507), nuclear energy consumption with the minimum (0.573) and maximum (8.680), economic growth with the minimum (2.904) and maximum (8.549), renewable energy consumption with the minimum (1.004) and maximum (7.549), and non-renewable energy consumption with the minimum (1.126) and maximum (7.549). (5.547).

Table 1: Data variables and sources

Variables	Symbol	Measurement	Data sources
Ecological footprint	EFP	CO_2 footprint per person	GFN
GDP	GDP	GDP per capita	WDI
Nulear Energy	NUE	Terawatt hours (TWh)	BP
Renewable energy	REC	Percentage of total final energy consumption	WDI
Non-renewable energy consumption	NRE	KG in oil equivalent per capita	WDI

Table 2: Descriptive statistics

Variables	Mean	St. Dev	Max	Min
EFP	3.215	2.581	6.507	1.570
GDP	10.438	7.458	8.549	2.904
NUE	2.658	2.778	8.680	0.573
RNE	7.549	2.549	7.549	1.004
NRE	4.470	2.438	5.547	1.126

Source: Authors' calculation

4. ESTIMATION STRATEGY AND RESULTS

4.1. Cross-sectional Dependence

The Cross-Sectional Dependence test is a statistical technique used in econometrics to assess the presence of dependence among observations in a cross-sectional data set. This type of dependence can lead to biased and inconsistent estimates in standard regression models, which assume independence among observations. The Cross-Sectional Dependence test aims to detect and correct for this type of dependence by comparing the results of different models that account for different forms of dependence. If the results of the test suggest the presence of cross-sectional dependence, adjustments to the standard regression model can be made to account for this dependence and produce more accurate and reliable results. (Breusch and Pagan, 1980; Pesaran, 2021) scaled LM; (Baltagi et al. 2012) bias-corrected scaled LM and (Pesaran, 2021) CD are used in this study to test for cross-sectional dependency.

In this study, the cross-sectional dependence (CSD) tests developed by Friedman, Frees, Pesaran, and Breusch and Pagan are utilized in order to determine whether or not the model under investigation has CSD. Table 3 contains the findings that were obtained from the CSD testing. According to the results of this research, it appears as though all of the variables show statistically significant evidence of CSD in the series. The interwoven nature of the economies of the countries that produce nuclear energy in the world economy is the root cause of the probable emergence of this CSD dilemma. This suggests that any change in the fundamental variables of one nation may have impacts that ripple out into other nations if there is a disturbance in those variables. Because of the spillover effects, the series is dependent across cross-sectional boundaries.

4.2. Panel Unit-root Tests

If a panel data series (a collection of many time series for distinct cross-sectional units like companies, countries, or regions) has a unit root, it is non-stationary and exhibits a trend that makes it challenging to predict the long-run relationships among the variables in the series. It is important to check for unit roots in panel data before undertaking regression analysis since a non-stationary time series can cause skewed and inconsistent results. This research used a number of panel unit-root tests, including the cross-sectional augmented Dickey-Fuller (CADF) and the cross-sectional augmented IPS (CIPS), to examine this concern (Pesaran, 2021).

The results of the panel unit root tests are presented above in Table 4 and it shows the results of the the CIPS and the CADF unit root tests. All variables in the first difference show evidence against the null hypothesis of stationarity, supporting the existence of a unit root as opposed to non-stationarity. According to panel stationary tests, all series have a unit root at the first difference I(0) but no unit root at I(1), according to panel stationary tests. It confirms the feasibility of moving on to estimate long-run cointegration and elasticity.

4.3. Westerlund Cointegration Method

The Westerlund cointegration (Westerlund, 2007) method is a statistical technique used in econometrics to test for cointegration between time series variables. Cointegration refers to a long-run relationship between variables, meaning that their relative changes move together over time. The Westerlund method is a panel data-based approach that is particularly useful in analyzing cross-sectional dependence among multiple time series. It employs a panel unit-root test to test for the presence of a common trend among the variables, and then uses the result to test for cointegration. The method is useful for estimating long-run relationships between variables in large datasets, and for analyzing the interdependence between variables over time.

Table 5 above illustrates the Westerlund cointegration test results for groups (Gt and Ga) and panels (Pt and Pa). Group and panel results indicate a long-term link in between the vaiables throughout nuclear energy-producing countries. Since the panel long-run cointegrated test suggests a long-term connection between variables, second-generation panel techniques can be used to estimate long-run elasticity.

4.4. Long-run Elasticity

The augmented mean group (AMG) strategy is a method for estimating panel data models, which are used to analyze data collected on multiple individuals or units over multiple time periods. The AMG strategy involves augmenting the mean group estimator, which is commonly used for panel data analysis, with additional information from the time-series dimension of the data. This is achieved by exploiting the relationship between the mean and individual deviations from the mean, and by considering the cross-sectional dependence in the data. The AMG strategy (Eberhardt and Bond, 2009) provides consistent and asymptotically normal estimators.

The findings of the empirical research on long-run elasticity estimations are presented in Table 6. If everything else remains the same, it would appear that the use of nuclear power would have a negative impact on the ecological footprint. For example, a one percent increase in the deployment of nuclear energy would result in a 0.3515% reduction in the ecological footprint over the long term in the top nuclear energy-producing countries. The findings of this study provide empirical evidence of These findings are consistent with the findings and conclusions of (Dong et al., 2018; Hassan et al., 2020; Saidi and Omri, 2020; Mahmood et al., 2020). In addition, the long-term effects of certain independent factors on the ecological footprint in these countries throughout the course of the specified time period were presented in Figure 1.

4.5. Dumitrescu-hurlin Panel Causality Test

The Dumitrescu-Hurlin (D-H) panel causality test (Dumitrescu and Hurlin, 2012) is a statistical method used in econometric modeling to examine the causality relationship between two variables in a panel dataset. The panel dataset refers to a data set that contains

Table 3: CSD test results

Series	BP-LM	PS-LM	BCS-LM	P-CSD
	Stat.	Stat.	Stat.	Stat.
EFP	1982.66*	85.65*	71.96*	41.23*
GDP	4001.78*	196.87*	185.88*	68.10*
NUE	3018.37*	169.11*	137.98*	62.21*
RNE	1809.06*	89.96*	86.63*	40.56*
NRE	2734.44*	145.86*	132.77*	52.01*

*Indicates the significance level at 1%. CSD: Cross-sectional dependence

Table 4: Unit root test results

Variable	CIPS		CADF	
	I (0)	I (1)	I (0)	I (1)
EFP	−2.45	−4.98*	−3.60	−2.85*
GDP	−2.50	−4.71*	−3.95	−2.42*
NUE	−2.56	−4.64*	−3.91	−2.98**
RNE	−1.96	−4.10*	−3.06	−2.84*
NRE	−1.66	−5.32*	−3.52	−3.01*

* and ** indicates the significant at 1% and 5% respectively. CIPS: Cross-sectional augmented IPS, CADF: Cross-sectional augmented dickey-fuller

Table 5: Westerlund cointegration test results

Statistics	G_t	G_a	P_t	P_a
Values	−2.53*	9.28**	−14.61*	−28.25*
Z-values	−2.33	1.953	−3.99	1.56
P-values	0.000	0.085	0.000	0.000

*and ** indicates the significant at 1% and 5% respectively

Table 6: Long-run elasticity estimates test results

Variable	AMG estimator		CCEMG estimator	
	Coeff.	Prob.	Coeff.	Prob.
GDP	0.2595*	0.0000	0.3800*	0.0000
GDP^2	−0.4901*	0.0000	−0.8231*	0.0000
NUE	−0.3515*	0.008	−0.3620*	0.0071
REC	−0.1865**	0.0169	−0.1956**	0.0213
NRE	0.9056**	0.076	1.5643**	0.015
Constant	−2.5012*	0.0000	−1.2478	0.0611
RMSE	0.028		0.018	

*and **Indicates the significant at 1% and 5% respectively and RMSE means Root mean squared error. AMG: Augmented mean group, CCEMG: Cross-sectional combined error mean group

Figure 1: Long-run regressor impact on the ecological footprint

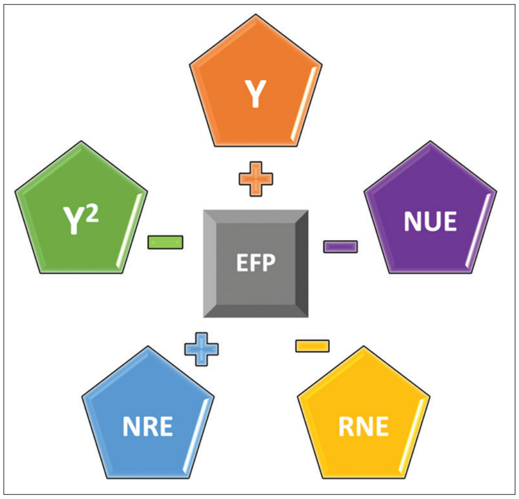

Table 7: Dumitrescu-hurlin panel causality test results

Null Hypothesis	W-Stat.	Stats.	Prob.
GDP⇎EFP	10.35*	13.872	0.000
EFP⇎GDP	5.76*	5.112	0.000
GDP^2⇎EFP	8.66*	6.834	0.000
EFP⇎GDP^2	6.91*	4.972	0.000
NUE⇎EFP	5.77*	3.852	0.000
EFP⇎NUE	5.84*	4.451	0.000
REN⇎EFP	4.87**	2.654	0.003
EFP⇎REN	4.12**	2.611	0.000
NRE⇎EFP	8.75*	9.875	0.000
EFP⇎NRE	5.32*	4.143	0.000

*, **Indicate the significance level at 1%, 5% and 10% respectively

observations for multiple units (such as countries, regions, or firms) over multiple time periods. The D-H panel causality test utilizes a time series and cross-section dependence (TSCD) framework to investigate the direction of causality between the variables. The test is widely used in empirical studies in economics and finance to identify the causal relationship between variables, such as economic growth and financial development, energy consumption and environmental pollution, and others. The test results provide valuable insights into the causal relationship between the variables, which can be useful in developing appropriate policies and interventions.

While the AMG and CCEMG estimators have been used to examine the long-term dynamic influence of the underlying variables, their ability to provide light on the causal connections between the examined series remains to be shown. As such, we used D-H panel heterogeneous non-causality test (2012). As a result, we learn the interconnected dynamics between ecological footprint, nuclear power, forms of both renewable and nonrenewable energy. Table 7 above showed the results of the D-H causality tests.

5. CONCLUSION AND POLICY RECOMMENDATIONS

5.1. Conclusion

The reduction of environmental pollution has become a widespread concern globally. With a growing population and increased production, the potential for environmental degradation is a pressing issue for both emerging and developed economies. To mitigate this, international agreements such as the Paris Agreement (COP-27) and the Kyoto Protocol have been established to encourage the reduction of environmental pollution and regulate average temperatures. The implementation of green technologies, clean energy infrastructure, and carbon pricing is crucial in reducing the environmental footprint. This study employs longitudinal data from 1990 to 2020 to assess the effects of economic growth, nuclear energy, non-renewable, and renewable energy consumption on the ecological footprint of economies that rely heavily on nuclear energy. A second-generation estimating method was used to take into consideration the potential for cross-sectional dependence. In the long term, the series were found to be related due to the cointegration analysis. Using cross-sectional combined error mean group (CCEMG) and augmented mean group (AMG) methodologies, we find that switching between nuclear and renewable energy sources has a hugely positive effect on the environment.

As a result of the research conducted here, some policy-level recommendations for balancing environmental and economic concerns in these nations have been identified. The research backs up the idea that nuclear energy can be used as a substantial source of energy in the long-term environmental policies and energy development programs that aim to fulfill the increasing energy needs around the globe. A deliberate effort should be made to encourage business and government to expand investments in the provision of nuclear energy sources and to remove barriers that limit the assessment of nuclear energy consumption without limiting their growth potential. It is imperative to launch the construction of nuclear energy facilities immediately. Additionally, private investors and domestic stakeholders should promote Public-Private Partnership (PPP) projects and address the obstacles faced by expanding investments in cleaner energy sources, thereby increasing their impact on alternative energy movements (Yang et al., 2022). To make matters worse for government officials and policymakers, private investors may express worries about governance-related risks. The results of this research show that the nuclear energy industry in each country is different, so the Paris Agreement (PA) should allow for open discussion on the topic if countries producing nuclear energy want to incorporate it. This would increase the efficiency of their efforts to reduce environmental pollution while decreasing costs. Nuclear power production necessitates stringent safety and security measures due to its potentially disastrous impact on the environment and on living creatures.

The EKC model can be used to develop policies to reduce the ecological footprint of economic development. For example, governments can focus on promoting environmentally-friendly technologies and practices, such as renewable energy and energy efficiency, and invest in research and development of new and innovative environmentally-friendly technologies. Additionally, governments can implement regulations and standards to reduce environmental degradation, such as emissions standards for vehicles and industries, and incentivize the use of environmentally-friendly technologies through tax credits or subsidies.

5.2. Policy Recommendations

Government of leading nuclear producing countries Implement and enforce strict regulations on the production, transportation, and disposal of nuclear fuel and waste to minimize the risk of accidents and leaks. Invest in the development of safe and responsible waste disposal methods to ensure that nuclear waste does not have long-lasting impacts on the environment. Implement safety measures to reduce the risk of accidents at nuclear power plants, such as backup systems and emergency response plans. Develop and implement plans for the decommissioning of old or decommissioned nuclear power plants, to minimize the environmental impact of these facilities. Increase public awareness and education (Katircioglu et al., 2020) about the risks and benefits of nuclear energy, and involve the public in the decision-making process surrounding nuclear energy. Encourage the development and use of renewable energy sources, such as wind, solar, and hydropower, to reduce the reliance on nuclear energy and the overall ecological footprint of energy production and consumption. Invest in research and development of new and innovative technologies that can reduce the ecological footprint of nuclear energy, such as advanced reactor designs, improved waste management methods, and new fuel sources. Foster international cooperation among nuclear energy producing countries to share best practices and technologies for reducing the ecological footprint of nuclear energy.

Governments can incentivize the development and deployment of renewable energy technologies, such as solar, wind, and hydropower, through tax credits, subsidies, or other forms of financial support, reducing the ecological footprint of energy production. Governments can incentivize the integration of renewable energy into the grid, through policies such as feed-in tariffs, to reduce the dependence on fossil fuels and lower the ecological footprint of energy production and consumption. Governments can provide financial and regulatory support to renewable energy industries, such as manufacturing and installation, to help create jobs and reduce the ecological footprint of energy production and consumption. Governments can implement renewable energy mandates, such as renewable portfolio standards, to ensure a certain minimum amount of renewable energy is used, reducing the ecological footprint of energy production and consumption. Governments can incentivize the use of energy-efficient technologies, such as LED lighting and smart grid systems, which can reduce energy consumption and lower the ecological footprint of energy production and consumption. Governments can promote public education and engagement on the benefits and challenges of renewable energy, to help increase public understanding and support for this energy source, reducing the ecological footprint of energy production and consumption. Governments can invest in research and development for new and innovative renewable energy technologies, such as next-generation solar panels and wind turbines, to further reduce the ecological footprint of energy production and consumption.

Encouraging the adoption of renewable energy sources, Governments of nuclear energy producing countries can promote the use of renewable energy sources, such as solar, wind, and hydropower, to reduce their dependence on non-renewable energy sources. Governments can encourage energy efficiency measures, such as energy-efficient appliances and buildings, to reduce energy consumption and greenhouse gas emissions. Governments can promote energy conservation by launching public awareness campaigns and implementing policies to encourage citizens to conserve energy. Governments can invest in research and development of clean energy technology to reduce the environmental impact of energy production and consumption. Governments can implement carbon pricing policies, such as carbon taxes, to incentivize the reduction of greenhouse gas emissions from the energy sector. Governments can support the development of green infrastructure, such as green roofs and urban forests, to absorb carbon dioxide and improve air quality. Governments can encourage the use of public transportation, such as buses and trains, to reduce the number of vehicles on the road and decrease emissions from transportation. Governments can encourage the development of sustainable communities, with low-carbon lifestyles and green spaces, to reduce the ecological footprint of their citizens. Governments can regulate and monitor the environmental impact of nuclear power plants to ensure that they are operating within safe and sustainable limits. Overall, the effect of nuclear energy producing countries on the ecological footprint will depend on a variety of factors, including the safety and disposal of nuclear waste, the emissions produced by nuclear energy, and the public and government policies surrounding nuclear energy.

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