

Article

Nexus between Nuclear Energy Consumption and Carbon Footprint in Asia Pacific Region: Policy toward Environmental Sustainability

Nihal Ahmed ¹, Farhan Mahboob ², Zeeshan Hamid ³, Adnan Ahmed Sheikh ⁴, Muhammad Sibte Ali ⁵, Waldemar Glabiszewski ⁶, Aneta Wysokińska-Senkus ⁷, Piotr Senkus ^{8,*} and Szymon Cyfert ⁹

¹ College of Economics & Management, Northwest Agricultural & Forestry University, Xianyang 712100, China

² School of Business, Bahria University, Karachi 75260, Pakistan

³ Department of Management Sciences, Shaheed Zulfiqar Ali Bhutto Institute of Science and Technology (SZABIST), Islamabad 44791, Pakistan

⁴ Department of Business Administration, Air University Multan Campus, Multan 60000, Pakistan

⁵ School of Business, Zhengzhou University, Zhengzhou 450001, China

⁶ Faculty of Economic Sciences and Management, Nicolaus Copernicus University, 87-100 Torun, Poland

⁷ Faculty of Management and Command, War Studies University Warsaw, 00-910 Warszawa, Poland

⁸ Institute of Social Sciences, SWPS University of Social Sciences and Humanities, 03-815 Warsaw, Poland

⁹ Institute of Management, Poznan University of Economics and Business, 61-875 Poznan, Poland

* Correspondence: senkus.piotr@gmail.com; Tel.: +48-60-464-5154



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Abstract: The distribution of energy sources is regarded to be an act of compassion in many of the Sustainable Development Goals outlined by the United Nations. In order to build a firm foundation for competitiveness and prosperity, nations should maintain equilibrium with the three key aspects of the global energy trilemma, which are energy affordability, energy access, and ecological balance. In light of this, the purpose of this research was to investigate the impact that nuclear energy, technological advancements, renewable energy, non-renewable energy, and natural resources have had on carbon footprints. We selected the top five nuclear energy countries by consumption in the Asia Pacific region, including China, India, Japan, Pakistan, and South Korea. We devised an exhaustive and all-encompassing empirical inquiry and used contemporary econometric methods. The second-generation panel's long-run cointegration promotes the idea of long-term relationships between the series. According to the data, using nuclear and renewable sources of energy significantly contributes to an improvement in environmental quality. On the other hand, advancements in technology and the use of energy sources that do not replenish themselves considerably decrease environmental sustainability. In addition, natural resources end up playing a negative role in the long term. The results of the panel's investigation into the chain of events that led to the development of nuclear power showed that the chain of events was unidirectional. In addition, there is causality that runs in both directions between technological innovation, renewable energy sources, non-renewable energy sources, and natural resources that have a carbon footprint. In light of this, it is recommended that these countries should combine energy policy actions and build energy strategy consistency by harmonizing the essential features of global nuclear energy in order to aid in the development of a well-calibrated energy structure.

Keywords: climate change; economics of nuclear energy source; nuclear energy consumption; carbon footprint; SDGs

1. Introduction

The threat of environmental change on health continues to be at the forefront of policy debates and is at the heart of the global agenda. For this reason, the notion of sustainable development is based on the three pillars of social, economic, and environmental quality sustainability, which have acquired great relevance for the survival of mankind.

Disturbances are caused by extreme weather occurrences in ecosystem variability, water availability, infrastructure decline, disruptions in food production, and an increase in morbidity and death rates [1]. Despite the fact that sustainable growth has been based on three mainstays, the importance of maintaining a healthy ecosystem has grown in this course due to the rapid dispersion of environmental variations and obstinate ecological circumstances [2]. Meanwhile, the ecological footprint is widely recognized as a linchpin indicator of sustainable development, a standard gauge of environmental deficit and environmental sustainability [1]. However, the literature explored the ecological footprint as an indication of environmental impact. It compelled researchers to examine the ecological dynamics resulting from human, social, geographical, and economic activity.

As a less polluting technology, nuclear energy ensures a pristine environment, hence enhancing human well-being. Nuclear energy provides and develops greater efficiency and adaptability. It provides access to low-cost, dependable, carbon-free energy for both industrialized and developing nations. Sixty gigatons of carbon emissions were avoided during the last 50 years due to nuclear energy [3]. This sort of energy transmits a massive amount of energy without emitting a significant amount of pollutants while in operation [3]. It is more economical to use nuclear power plants, provide dependable energy support, contribute to economic stability, and make a nation climate-resilient by protecting it from climate change. The initial capital expenses of the power plants are high, whereas their operational costs are low. As a result, costs associated with nuclear energy have, for the most part, been consistent and easy to anticipate throughout the last several decades. This is due to the fact that the cost structure of nuclear plants makes changes in nuclear power relatively unnoticeable. However, nuclear power plant energy production increased from 2563 to 2657 terawatt hours (TWh) in 2018 and 2019 [4]. Nuclear energy may also be used to reinstall non-renewable energy sources in a predictable, safe, secure, and economically sustainable way; hence, nuclear energy will be an essential component in the overall energy transition [5,6].

The benefits derived from nuclear power have raised the level of scrutiny of the environmental effect of nuclear energy use. Following the proclamation of the Paris Agreement (PA), nuclear energy use has reached a significant concentration. Several academics and experts [7,8] stated that using nuclear energy is a viable option that may be able to overcome the challenges of insufficient ecological resources and inadequate energy security. On the contrary, nuclear power plants need a significant amount of infrastructure construction [9], as well as hefty capital expenditures, both of which are inadequate in rising nations [10]. In spite of the fact that nuclear energy units are not directly responsible for a considerable amount of pollution, the relatively small infrastructure footprints of these facilities are superior to the environmental quality compensation they provide. In addition, nuclear power is a sham because of the various difficulties associated with it. Some of these difficulties include the off-site impacts of nuclear catastrophes, radiation disclosure, radioactive waste [3], as well as explosions [11]. Additionally, it was shown that conventional energy usage and reliance on foreign sources of energy do little to mitigate pollution when compared to the use of nuclear energy sources [12].

The endogenous growth theory elucidated the effects of technological advancements on the evolution of the link between economic growth and environmental deterioration. According to this theory, production procedures are improved by increasing the capacity of emission-free and environmentally friendly resources to replace emitting/dirty resources [13]. Such functions rely on residents' commitment to the environment; if their real income rises, they may devote more assets and resources to defense. If pollution levels fall as actual economic growth rises, technological breakthroughs will play a key role, and the drop in pollution would be the result of "induced innovation", according to Hicks's theory. Whether a patent application as a whole may be seen as a predictor of eco-friendly economic growth is a further challenge that arises in this circumstance from an ecological point of view. Most economic mediators are in agreement that the shift in technological innovation is the key to achieving sustainable economic and environmental growth. This has led to

an increased focus on improvement/innovations and their support. In this situation, the question to ask is what impact technological advancement has on reducing the environmental pollution. There were a number of researchers who achieved success in the field of energy on global, sectoral, and national scales. According to Usman et al. [1], technical breakthroughs are the primary engine of economic development, but their long-term effects on the environment remain uncertain. In one sense, a greater level of economic activity would lead to higher overall levels of energy consumption as well as perhaps increased levels of environmental degradation. As opposed to that, a groundbreaking innovation has the potential to make use of less energy resources, and as a result, it may help maintain the quality of the environment. The challenge is to determine which mesh result is the absolute one. In addition, fraudulent energy practices may be found in any business, not only the energy sector, indicating that energy theft is a problem across the board.

Thus far, many people have responded to the energy crisis by offering their own solutions. Among the most important non-renewables are conventional energy sources such as oil, coal, and natural gas, which have been formed over millions of years. However, due to rising economic growth and global population, non-renewable have been rapidly depleted and are predicted to run out in the not-too-distant future. In addition, non-renewable does serious harm to the environment; hence a shift back to greener energy sources is inevitable [1]. Solar, geothermal, biomass, hydro, and wind power are only a few examples of renewable energy sources that may be used in their natural state [14,15]. Since cleaner energy supplies are both potentially unconstrained and vulnerable to the climate, they can be effectively utilized even while resources for non-renewable energy are scarce and the activities that can be made about non-renewable resources are likewise restricted. Furthermore, the use of renewable and alternative energy sources is seen as a top solution to issues related to energy improvement. Increased solar and wind energy competitiveness leads to a rapid expansion of the renewable energy sector [16]. One of the most dynamic, rapidly shifting, and ever-evolving industries in the world at present is the cleaner and alternative energy industry. The sector is now the driving force of global economic growth because of technological advancements, decreased costs, and the tremendous impact of new financial institutions. In particular, nations reached a consensus on how to deal with the intimidating effects of climate change via the widespread use of renewable energy technology.

With this context in mind, our investigation contributes to the existing literature by means of the following. Scientists looked at the connection between technological progress, energy use, and environmental deterioration from a wide variety of angles, using a wide range of modeling techniques, and generating a wide range of findings. However, none of them have looked at the connections between nuclear power and other factors such as technical progress, the availability of renewable and non-renewable sources of power, the availability of natural resources, or a country's carbon footprint. To my knowledge, no studies have looked at how technological progress may have contributed to this correlation. Because advances in technology could lead to the production of cleaner and alternative forms of energy at the same time that the risk of atmospheric contamination is reduced, the technological development parameter is one that should be evaluated as part of the relationship between nuclear energy utilization and carbon footprints. Therefore, the purpose of this research was to address this vacuum in the existing literature by responding to the following questions: If we want to lessen our impact on the environment, which is better: renewable energy or nuclear power among the leading nuclear power producers in the Asia Pacific region? Is there a substitutional or complementary relationship between nuclear power and renewable energy in lowering the carbon footprint? In order to find answers to these concerns, researchers use a wide range of estimating techniques in search of underlying long-term and causal relationships. A sustainable environment may ensure that the environment is protected over the long term, and the projected empirical results will help environmentalists, energy specialists, and development practitioners in rethinking and implementing policy implications that are environment-friendly and emission-free. Furthermore, central bodies and governments favoring investment in the nuclear energy

industry will find the current study beneficial. Figure 1 depicts the CO₂ emissions, and Figure 2 depicts the nuclear energy consumption in the selected Asia Pacific countries.

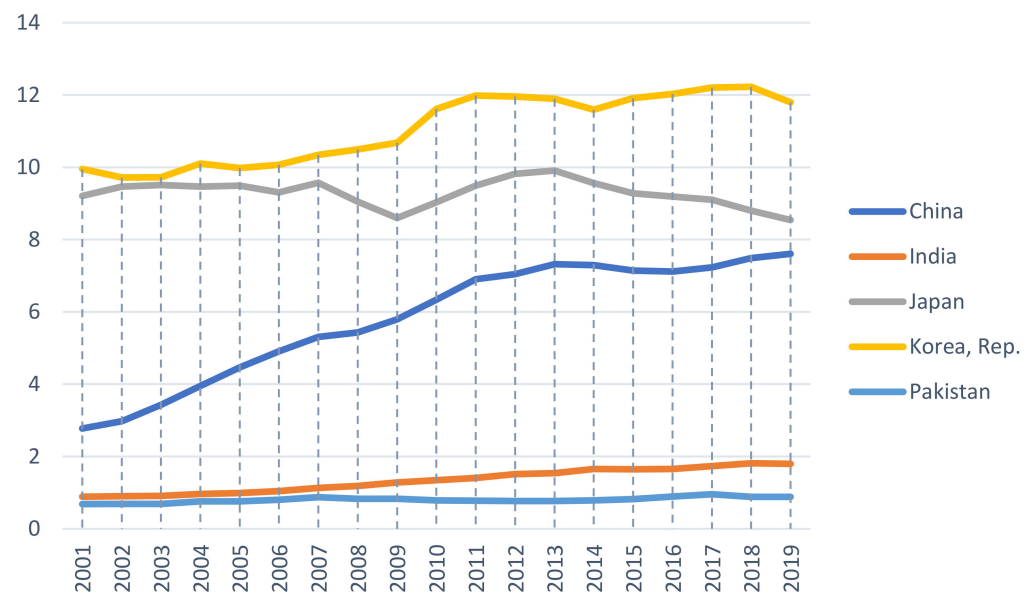


Figure 1. CO₂ emission in selected Asia Pacific countries source: Global footprint network [17].

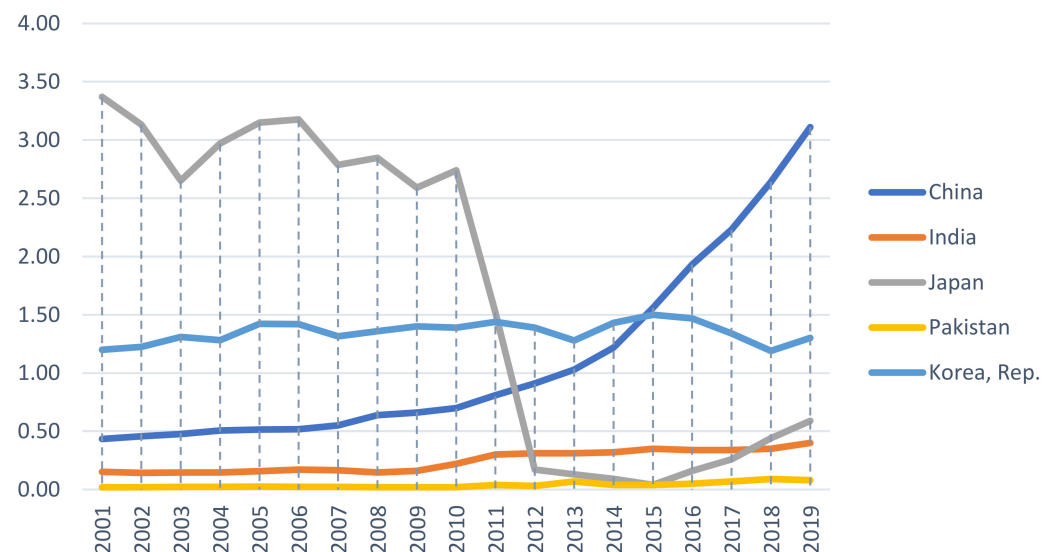


Figure 2. Nuclear energy consumption in selected Asia Pacific countries source: Global footprint network [17].

The remaining sections of this article are as follows: Section 2 discusses the literature review. Data sources and the econometrics methodology are discussed in the third section; empirical results make up the fifth section; and the conclusion, discussion, and policy recommendation are discussed in the final section.

2. Literature Review

Multiple studies demonstrated the empirical connection between natural resources, nuclear and renewable energy, non-renewable energy, technical innovation, and environmental degradation. In spite of this, the literature was segmented into pairwise connections based on previously expected outcomes between the selected variables.

2.1. The Nexus between Nuclear Energy and the Environment

Recent research has focused on the many ways in which the implementation of nuclear power plants affects the quality of the atmosphere. In addition, a number of studies included the connection between environmental degradation and nuclear energy use [8,18,19]. By considering the importance of sustainable energy, however, several researchers studied the extent to which environmental deterioration and economic development may be linked by including nuclear energy [6,20]. Nuclear power is superior to other forms of clean and green energy under some severe circumstances than other renewable energy sources of preventing environmental harm [1,19,21]. Hassan et al. [22] discovered an inverse relationship between the use of nuclear power and the degradation of the surrounding ecosystem in the BRICS region. In addition, the use of nuclear energy is beneficial for halting climate change and reducing environmental pollution [23–25]. In addition, [9] examine a study on Pakistan's economic development, carbon emissions, and nuclear energy.

2.2. The Nexus between Technological Innovation and the Environment

It is difficult to ignore the ways in which technological advancement and scientific research have distorted people's financial and economic decisions. However, this transformation also made environmental sustainability concerns in places around the globe with extensive technological innovation penetration. By using panel, cross-sectional, and time-series, a portion of the extant investigated the factors influencing the link between technological advancement and environmental virtuosity. Zhang & Liu [26], for instance, studied the relationship between environmental pollution and technological innovations by using a Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model to China's regional data from 2000 to 2010. China's pollution levels decreased due to technological innovations, as seen by the dynamic findings of the panel method. On the other hand, Añón Higón et al. [27] studied an inverted U-shaped relationship between technological innovation and ecological pollution. By using data from developing and wealthy countries, this study examined the unequal relationship between technological innovation and environmental pollution.

2.3. The Nexus between Renewable and Non-Renewable Energy Usage and the Environment

Several empirical study papers in the available literature discovered that the use of non-renewable energy diminishes ecological performance while the use of renewable energy preserves the ecosystem. Numerous empirical researchers, such as [1] for Pakistan and [2] for the PIIGS countries, support this prediction. Algeria, Ref. [28], in their study, concluded that fossil fuel has an adverse effect on the environment; however, it is also examined that cleaner energy significantly mitigates environmental pollution. Ref. [29] employed the VECM approach and concluded that renewable energy provides a viable means to reduce Malaysia's pollution level.

In contrast, despite the fact that the vast bulk of the current literature supports the adverse relationship between renewable energy sources and carbon emissions, some research produced findings that are inconsistent with the aforementioned studies. Some writers find that the usage of both non-renewable and renewable energy significantly increases environmental degradation [30–32].

2.4. The Nexus between Environmental Degradation and Natural Resources Rent

The excessive deployment, exploitation, and depletion of natural resources and emissions constitute a vast area of study in the current literature on the environment and economic growth. As a result, researchers, legislators, and environmentalists placed a greater emphasis on natural resources and environmental deterioration in the present decade. Usman et al. [1] demonstrated that renewable energy significantly lower pollution levels, while globalization, non-renewable, and economic expansion contribute to rising pollution levels. Moreover, all research factors promote economic expansion. Ref. [33] discovered the adverse relationship between natural resource use and carbon emissions when

technological advancement was included. In their investigation of China's ecological footprint, Ref. [34] showed that increased use of natural resources precedes a rise in pollution. The literature indicates that the use of renewable energy helps decrease emissions, but the use of non-renewable energy increases the ecological and carbon imprint of the atmosphere. Moreover, the exploitation of natural resource rents contributes to the long-term increase in carbon emissions.

Reduced greenhouse gas emissions can help mitigate climate change's destructive effects, but only if the globe weans itself off fossil fuels quickly. In order to meet the world's demand for safe, reliable, and cheap power, nuclear energy is a viable option because of its low carbon footprint and rapid scale-up for widespread use. The study will help policymakers and government bodies to understand the significance of using nuclear energy that can contribute to solving one of the greatest challenges faced by humankind. The importance of nuclear energy consumption in lowering carbon footprints necessitates research that investigates the long-term and causal linkage between nuclear energy consumption, carbon footprints, natural resources, renewable and non-renewable energy, and technological innovations in high nuclear energy consumption in the Asia Pacific region. In addition, it is essential to recognize that an explanation of renewable energy has the potential to bring about a sustainable environment by reducing the amount of CO₂ emissions that are released into the environment. Using nuclear energy in the decarbonization agenda, together with technical advancements and natural resources, would have positive ecological consequences and be beneficial for a long-term sustainable environment, as argued for in the current research. Hence, more empirical research is needed to determine whether using nuclear energy sources in economic, social, and other sectors benefits the climate.

3. Materials and Methods

3.1. Variables and Data Sources

The core objective of this study was to examine the linkage between carbon footprint, nuclear energy, renewable energy, non-renewable energy, technological innovations, and natural resources. This study includes the top six nuclear energy countries by consumption in the Asia Pacific region, including China, India, Japan, Pakistan, and South Korea. The study used annual data for the time span from 2001 to 2019. Table 1 provides the description of the selected variables.

Table 1. Description of the variables.

Variables	Abbrev	Unit	Source
Carbon footprint	CF	Global hectares per person	Global footprint network
Nuclear energy consumption	NEC	Terawatt hours (TWh)	World Energy British Petroleum Statistical Review
Technological innovation	TI	Total patent applications	World Development Indicators
Renewable energy	RE	Percentage of total energy consumption	
Non-renewable energy	NRE	Kilogram in oil equivalent per capita	
Natural resources	NR	Percentage of GDP	

Source: [16,17,35].

The Patent Cooperation Treaty (PCT) process has the authority to file patent applications globally. All the employed variables are transformed into logarithmic form. Among the numerous kinds of transformations used to alter skewed data to near normalcy, the log transformation is likely the most used. Another advantage is that it minimizes data variability, especially in datasets with outlier observations.

3.2. Model Development and Methodological Framework

This research began by examining cross-sectional dependencies. Cross-sectional dependence is an important statistic for understanding geographic effects, unknown mutual shocks, and the existence of social networks. This is achieved by using Pearson's CD (cross-sectional dependence) test. The null hypothesis states that there is no cross-sectional dependency between the variables, while the alternative hypothesis verifies the existence of cross-sectional dependence.

The research utilized three unit-root tests, including the Pesaran CADF, Breitung and Das, and CIPS tests. The tests are based on group-mean estimation and test statistics with standard normal distribution.

This research also used Westerlund and Edgerton's [36] dynamically based error correction panel cointegration test, which may tackle the issues of cross-sectional and heterogeneity. The null hypothesis is that there is no cointegration, as opposed to the alternative hypothesis that the cointegration relationship exists. If the Z-statistics probability value was smaller than the critical value, we adopted the alternative hypothesis of cointegration.

This research also applies the "panel dynamic ordinary least square" (PDOLS) and "completely modified ordinary least square" (FMOLS), which are recognized for producing more reliable findings. The FMOLS approach, a nonparametric methodology, has the benefits of reducing simultaneous bias, sequence correlation, and endoplasmic error. In order to confirm the accuracy and dependability of the test results, the authors of the long-term impact test utilized a supplementary method known as DOLS. FMOLS and PDOLS are represented by Equations (1) and (2), respectively.

$$\hat{\beta}_{FMOLS} = \left(\sum_{i=1}^N \hat{L}_{22i}^{-2} \sum_{t=1}^T (x_{it} - \bar{x})^2 \right)^{-1} \sum_{i=1}^N \hat{L}_{11i}^{-1} \hat{L}_{22i}^{-1} \left(\sum_{t=1}^T (x_{it} - \bar{x}) y_{it}^* - T \hat{\delta}_i \right) \quad (1)$$

where $\mu_{it}^* = \mu_{it} - \frac{\hat{L}_{21i}}{\hat{L}_{22i}} \Delta x_{it}$, $\hat{\delta}_i = \hat{\Gamma}_{21i} \hat{\Omega}_{21i}^0 - \frac{\hat{L}_{21i}}{\hat{L}_{22i}} \left(\hat{\Gamma}_{22i} + \hat{\Omega}_{22i}^0 \right)$, and $\hat{L}_i$ was the lower triangulation of $\hat{\Omega}_i$.

$$\hat{\beta}_{DOLS} = \frac{1}{N} \left[\left(\sum_{t=1}^T Z_{it} * Z'_{it} \right)^{-1} \left(\sum_{t=1}^T Z_{it} * \hat{W}_{it} \right) \right] \quad (2)$$

where $Z_{it} = [X_{it} - \bar{X}_i, \Delta X_{it-ki}, \dots, \Delta X_{it+ki}]$ is the vector of regressors, and $\hat{W}_{it} = W_{it} - \bar{W}_i$.

Fourth, the research verifies the short-term correlation between variables using the causality test developed by Dumitrescu and Hurlin [37], which is crucial for policy decisions. The Dumitrescu–Hurlin panel causality test is a straightforward adaptation of the Granger non-causality test for non-homogeneous panel data models with constant coefficients. Dumitrescu and Hurlin examined heterogeneity from two angles: the heterogeneity of the regression model used to analyze Granger causality and the variability of causal links. This test needs the series to be level and steady. This method takes cross-sectional dependence among sample countries into consideration. The Dumitrescu–Hurlin test may predict cross-section dependence and independence situations. The typical panel Granger causality tests demonstrate that if there is a causal relationship in a subset of the variable due to a lack of cross-sectional data, it is due to the homogeneous null hypothesis. The null hypothesis asserts that there is no Granger causality connection between cross-sections, while the alternative hypothesis asserts that there is at least one Granger causality link between cross-sections [37].

Fifthly, the pooled mean group-autoregressive distributed lag (PMG-ARDL) model was employed to analyze the relationship between the previously listed variables. This study's empirical model is stated as follows:

$$CF_{it} = \beta_0 + \beta_{1i} NE_{i,t-i} + \beta_{2t} TI_{it} + \beta_{3t} RENER_{it} + \beta_{4t} NRENER_{it} + \beta_{5t} NRR_{it} + \varepsilon_{it} \quad (3)$$

where i is used for country, and t denotes the period. CF denotes the carbon footprint, NE is the nuclear energy, TI is the technological innovation, RE and NRE represent renewable and non-renewable energy, and NR denotes natural resources rent. Furthermore, $\beta_0, \beta_1 \dots \beta_4$ are the parameters to be computed, and ε_{it} is the residual term. The study used the pooled mean group-autoregressive distributed lag (PMG-ARDL) model to investigate the short and long-run impact. According to Pesaran and Smith [38], a conventional approach such as GMM estimators is considered inconsistent and potentially misleading unless the slopes are identical. Specification of the PMG-ARDL model is expressed as follows:

$$\Delta CF_{it} = \alpha_0 + \sum_{a=1}^{m-1} \beta_{ia} \Delta CF_{i,t-a} + \sum_{b=0}^{n-1} \beta_{ib} \Delta NE_{i,t-b} + \sum_{c=0}^{p-1} \beta_{ic} \Delta TI_{i,t-c} + \sum_{d=0}^{q-1} \beta_{id} \Delta RE_{i,t-d} + \sum_{e=0}^{r-1} \beta_{ie} \Delta NRE_{i,t-e} + \sum_{f=0}^{s-1} \beta_{if} \Delta NR_{i,t-f} + \sigma_1 CF_{i,t-1} + \sigma_2 NE_{i,t-1} + \sigma_3 TI_{i,t-1} + \sigma_4 RE_{i,t-1} - \pi NRE_{i,t-1} - \pi NR_{i,t-1} + \varepsilon_{it} \quad (4)$$

where Δ is used for difference operator, β is the short run parameter, σ represents the long run parameter, ε_{it} represents the residual term.

4. Results and Discussion

This section gives detailed empirical results and discusses the outcomes of these results. Table 2 provides the descriptive statistics of the variables.

Table 2. Descriptive statistics.

Variable	Minimum	Mean	Maximum	Std. Dev.
CF	0.043	4.8075	9.572	5.013
NE	0.023	4.698	9.373	3.521
TI	1371	863,306.5	1,725,242	261,242
RE	0.532	20.0765	39.621	7.612
NRE	47.532	80.1255	112.719	14.627
NR	0.026	13.134	26.242	5.613

Note: Author(s) depictions.

The results of the variables' unconditional correlations were the starting point of our results. According to Table 3 results, the carbon footprint correlates positively with all independent factors (nuclear energy, technological innovation, renewable energy, non-renewable energy, and natural resources). Similarly, technical innovation has a positive link with nuclear energy, but nuclear energy has a negative correlation with natural resources, non-renewable energy, and renewable energy. In addition, a negative link exists between technical innovation and renewable energy and natural resources, but a positive association exists between technological innovation and non-renewable energy. Furthermore, renewable energy is related adversely to non-renewable energy and natural resources. Finally, non-renewable energy has a favorable correlation with natural resources.

Table 3. Unconditional correlations among the variables.

Series	CF	NE	TI	RE	NRE	NR
CF	1					
NE	0.642	1				
TI	0.607	0.264	1			
RE	0.609	−0.242	−0.139	1		
NRE	0.799	−0.235	0.305	−0.450	1	
NR	0.747	−0.226	−0.148	−0.497	0.391	1

Note: Author(s) depictions.

The consistency and impartiality of traditional panel estimators may be compromised if the cross-sectional dependency is neglected due to geographical variables or particular unknown cofactors. These three methods from Table 4 were used to verify the results of the cross-section dependency test in order to improve the accuracy of the test's results.

According to Table 4, the favorable Pesaran CD test, the Pesaran scaled LM test, and Breusch and Pagan LM test are statistically significant at the 1% level. The importance of this potential CSD problem stems from the interconnectedness of nuclear energy-producing nations inside the global environment. In light of the spillover effects, the series is cross-sectionally dependent. All three applied approaches accept the alternate hypothesis, which indicates that there is no cross-sectional dependence.

Table 4. The results of cross-sectional dependence tests.

Variables	Pesaran Scaled LM		Pesaran CSD		Breusch-Pagan LM	
	Statistics	Prob. Value	Statistics	Prob. Value	Statistics	Prob. Value
CF	145.707	<0.01	32.785	<0.01	1910.51	<0.01
NE	157.039	<0.01	34.041	<0.01	877.15	<0.01
TI	190.558	<0.01	45.795	<0.01	2102.68	<0.01
RE	142.822	<0.01	32.136	<0.01	1872.68	<0.01
NRE	153.930	<0.01	33.366	<0.01	859.787	<0.01
NR	186.785	<0.01	44.888	<0.01	2061.05	<0.01

Source: Author(s) calculation.

This research then used panel unit root tests to determine the stationarity property of each data series. It is essential to examine the data series for unit root because using non-stationary data variables may result in skewed information and provides spurious results. Consequently, it is essential to examine the data series for unit roots. The study used three second-generation panel unit root tests, namely the favorable CIPS test, the Breitung and Das test, and the Pesaran CADF. Table 5 displays the results of unit root tests conducted on panel data. The findings of the selected unit root tests have probability values of less than 5% at the first difference, which indicates that all the selected variables are at least significant at the first difference.

Table 5. Second generation panel unit root findings.

Series	Breitung and Das Test		CIPS Test		CADF Test	
	Level	First Diff	Level	First Diff	Level	First Diff
<i>Intercept</i>						
CF	−2.81 *	−4.78 **	−2.09	−3.19 **	−2.05	−3.02 **
NE	−2.16	3.87 ***	−2.38	3.60 **	−3.28	4.33 ***
TI	−2.41	−3.22 **	−0.94	−3.05 **	−2.56	−3.42 **
RE	−2.41	−3.23 **	−2.49	−3.59 **	−2.80	−3.73 **
NRE	−2.73	−3.64 **	−1.24	−3.10 **	−1.98	−2.85 **
NR	−2.10	3.75 **	−2.32	3.50 **	−3.19	4.20 ***
<i>Intercept and trend</i>						
CF	−1.37	−4.82 ***	−2.47	4.04 ***	−1.08	−2.91 **
NE	−2.25	3.29 **	−3.39	4.69 ***	−2.59	3.80 **
TI	−2.60	−3.92 **	−2.75	4.27 ***	−2.16	−3.83 **
RE	−1.20	−2.82 **	−2.16	−4.47 **	−2.37	−3.96 ***
NRE	−1.33	−4.68 ***	−2.39	3.93 **	−1.05	−2.42 *
NR	−2.19	3.20 **	−3.29	4.54 ***	−2.51	3.68 **

*, **, and *** indicate 10%, 5%, and 1% level of significance.

The results of panel unit root tests confirmed that all the variables are at least significant at the first difference; hence, the cointegration test was performed in this study. This research applied the Westerlund and Edgerton [36] test, which is a dynamically based error correction panel cointegration test that can battle heterogeneity and cross-dependence. Due to the properties of the second-generation cointegration test, it provides trustworthy and more precise information on the cointegration relationship between the variables over

the long term. The null hypothesis is the absence of cointegration between the variables, as opposed to the alternative hypothesis, which indicates the presence of a cointegration relationship between the variables. Since the Z-statistics probability value is smaller than the critical value, we adopted the cointegration alternative hypothesis. Table 6 provides the results of the error correction panel cointegration test. The provided results conclude that the cointegration relationship exists.

Table 6. Westerlund second-generation error correction panel cointegration test.

Statistics	Values	Z-Values	p Values
G_t	−4.30	−5.49	<0.01
G_a	−18.15	−7.91	<0.01
P_t	−9.62	−5.49	<0.01
P_a	−14.20	−10.40	<0.01

Source: Authors' calculation.

The estimated results of the “panel fully modified ordinary least squares” (FMOLS) and “panel dynamic ordinary least squares” (PDOLS) models are shown in Table 7. Both tests offer the size and sign of the association between the specified variables over the long term.

Table 7. Results of the PFMOLS and the PDOLS estimations.

Dependent Variable Log Carbon Footprint							
PFMOLS				PDOLS			
Series	Co-eff	t-Stats	Prob-Value	Series	Co-eff	t-Stats	Prob-Value
NE	−0.30	−3.74	0.009	NE	−0.40	−4.13	0.008
TI	0.18	3.35	0.033	TI	0.15	8.42	0.000
RE	−0.22	−5.29	0.000	RE	−0.12	−7.73	0.002
NRE	0.99	2.01	0.084	NRE	1.13	2.74	0.017
NR	0.14	2.41	0.026	NR	0.01	2.24	0.077

Source: Author(s) calculation.

Nuclear energy and renewable energy have negative coefficients, while technical innovation, non-renewable energy, and natural resources have positive coefficients. In addition, nuclear energy and renewable energy are statistically significant at the 1 percent level, whereas technical innovation, non-renewable energy, and natural resources are statistically significant at the 5 percent level.

Based on the results of the aforementioned experiments, it can be stated that nuclear energy usage may have a negative impact on carbon footprint. This result shows that, since nuclear energy produces almost no carbon emissions, replacing traditional power plants that use non-renewable energy with nuclear power plants could help reduce environmental humiliation caused by nuclear energy use to a vast extent. These findings are consistent with those of [9,19,21,22]. However, it is imperative to note that, despite the fact that nuclear energy plays a significant role in reducing carbon emissions, organizing nuclear power units always involves a few risks. These risks are largely dependent on broad cross-country differences in political, economic, and social factors. Despite the fact that nuclear energy plays a significant role in reducing carbon emissions, organizing nuclear power units always involves a few risks [18,24]. When considering the effects on human health and the environment that nuclear power and other forms of energy consumption and production have, these risks should be evaluated, and efforts should be made to lessen their impact (e.g., renewables and non-renewable energy sources). Nonetheless, it is necessary to keep in mind that nuclear power demands protection and cost management to avoid any catastrophe that might possibly harm humans and the environment. Consequently, while making policy decisions about nuclear power, it is important to carefully evaluate not just its benefit/advantage in reducing carbon footprint but also a number of other

features, such as its latent dangers. Moreover, the generation of power from nuclear sources necessitates an enormous concentration pact for safety precautions. In order to avoid unanticipated negative effects on human health and the natural environment, radioactive waste installation and management in nuclear power plants need to be handled with extreme caution [8]. A further benefit of nuclear energy is that it has tremendous commercial potential [1]. The spread of nuclear energy ensures economic prosperity and energy security. As part of this endeavor, the estimated evidence suggests that a strategy supporting the acquisition and promotion of nuclear energy utilization as well as the renewable energy deployment growth in the energy mix could assist these countries by achieving their energy security objectives as a complement to the Sustainable Development Goals as well as providing a signal of commitment.

This technological innovation result is consistent with [38]. The findings demonstrate that the relationship between carbon footprint and technological development is beneficial in the long term. Due to rapid industrialization, it may be assumed that scientific advancements and environmental regulations in these nations are mostly geared toward achieving industrial growth, which is achieved at the expense of the environment by creating ambient environmental contamination. Real economic growth and environmental deterioration are both impacted by the technological modernity initiated in these nations, and it is expected that this will have a negative impact on sustainable development. That being said, the present tactics in these nations must be restructured to internalize the negative externalities caused by the actual trajectories of growth/expansion and ensure environmentally sound growth.

In addition, Carbon emissions are also negatively connected to renewable energy, despite its environmental benefits and its importance as a source of cleaner, greener energy. This implies that the consistent use of renewable energy sources is effective in reducing the carbon footprint in nations with a high nuclear energy production rate, hence preserving the quality of the natural environment. These outcomes are comparable to those of an earlier trial [1]. Utilizing alternative and renewable energy entails emission-free characteristics; hence, it does not leave a carbon imprint on the environment. These highly nuclear energy-producing nations are on the correct track toward reaching sustainable development objectives via the inclusion and evolution of clean energy technology, as their usage of alternative and renewable energy sources is shown to have a negligible impact on the environment. In addition, these data demonstrate that these nations are transitioning from non-renewable energy sources to cleaner alternatives that are more effective at reducing their carbon footprint. For a sustainable environment, these nations must install cleaner technologies and provide cash for advanced technology to increase the consumption of renewable energy. At present, the nuclear energy-producing nations are focusing on achieving their clean energy goals by reducing the cost of financing, decreasing taxes, and increasing financial support for clean energy projects.

Non-renewable energy contributes to an increase in carbon footprint in nations with a high nuclear energy production rate. Non-renewable energy sources, such as coal, jet fuel, petroleum, etc., have long been acknowledged in the scientific literature as the primary contributor of carbon and other greenhouse gases to atmospheric pollution. In contrast to the unsustainable and limited nature of renewable energy sources, such as fossil fuels, which also contribute to the changing of the climate and global warming through increased greenhouse gas emissions, renewable energy sources are both abundant and widely available, and they also help to reduce environmental degradation. By considering the energy-intensive circumstances of countries that produce a great deal of nuclear energy, increasing one's level of energy expertise in reducing carbon emissions by encouraging the use of energy-saving technologies is yet another policy choice, which is one of the most important green growth inputs for the countries [34]. According to the works of [39] for the United States, [40] for BRICS countries, and [1] for BRICS-T countries, continuing to use these fossil fuel energy sources may limit further ecological devastation due to carbon emissions. It was shown that there is a much larger positive magnitude of the use of non-renewable energy sources than there is a negative magnitude of the deployment of

renewable and nuclear energy sources with regard to the carbon footprint of the area as a whole. This research indicates that the utilization of non-renewable energy decreases environmental quality.

Finally, it was discovered that the use of natural resources has a beneficial influence that is statistically significant and has a positive effect on the carbon footprint. This illustrates that the mining of natural resources causes environmental harm in nations with a high nuclear energy production rate. This is helpful because extracting natural resources enhances economic expansion directly, which in turn raises environmental damage. Refs. [14,41] found comparable results for the BRICS group and 16 European Union nations. According to recent research by [14], the industrialization process leads to the overuse of natural resources, which significantly increases the region's pollution levels. In addition, an increase in extractive activity has the potential to provide a number of benefits for economic development, but it also has a negative impact on the environment. Mineral mining, oil, coal, and natural gas may be to blame for biodiversity loss, environmental disparity, deforestation, and soil erosion in these nations, according to this research. Therefore, initiatives to increase the efficiency of natural resource exploitation and reduce their negative impact on the environment are vital.

Table 8 provides the findings of the Dumitrescu and Hurlin Causality approach. The empirical findings reveal only a unidirectional causality between nuclear energy usage and carbon footprint. This illustrates how even a little shift in nuclear energy use may have a noticeable impact on one's ecological footprint. The results of long-run estimates, which are more important for policymaking authorities and governing, are also consistent with this estimated conclusion. The result is in line with the findings of [6] for the United States, [7] for 30 distinct economies, and [19] for OECD nations. These nations may reduce environmental damage by efficiently managing nuclear energy extraction. In addition, unidirectional causal links were shown between nuclear energy use and renewable energy use, renewable and non-renewable energy use, and natural resources.

Table 8. Dumitrescu and Hurlin Causality Analysis.

	Null Hypothesis		W-Stat.	Zbar-Stat.	p-Value
CF	x→	NE	2.940	0.875	0.399
CF	x→	TI	5.078	3.537	<0.01
CF	x→	RE	4.452	2.758	<0.01
CF	x→	NRE	6.784	5.661	<0.01
CF	x→	NR	4.345	2.625	<0.05
NE	x→	CF	6.315	5.077	<0.01
NE	x→	TI	6.078	4.782	<0.01
NE	x→	RE	5.105	3.571	<0.01
NE	x→	NRE	10.364	10.117	<0.01
NE	x→	NR	2.112	0.155	0.897
TI	x→	CF	5.507	4.071	<0.01
TI	x→	NE	6.621	5.458	<0.01
TI	x→	RE	5.972	4.650	<0.01
TI	x→	NRE	5.185	3.670	<0.01
TI	x→	NR	1.756	0.598	0.570
RE	x→	CF	8.829	8.206	<0.01
RE	x→	NE	2.227	0.012	0.911
RE	x→	TI	3.617	1.719	0.094
RE	x→	NRE	6.003	4.688	<0.01
RE	x→	NR	4.944	3.370	<0.01
NRE	x→	CF	4.236	2.489	<0.05
NRE	x→	NE	4.607	2.951	<0.01
NRE	x→	TI	5.239	3.738	<0.01
NRE	x→	RE	4.397	2.689	<0.01
NRE	x→	NR	5.239	3.737	<0.01
NR	x→	CF	4.712	3.081	<0.01
NR	x→	NE	1.504	0.911	0.380
NR	x→	TI	2.627	0.487	0.647
NR	x→	RE	2.251	0.018	0.906
NR	x→	NRE	1.090	1.427	0.165

Note: x→ denotes no causality relationship. source: authors' calculation.

Furthermore, a bidirectional causal relationship was discovered between natural resources, renewable and non-renewable energy, and technological innovation with an ecological footprint. The results are consistent with the findings of [40,41] for the European Union and the BRICS area, respectively. From the empirical results, it is recommended that any increase in spending on technological innovations that replace fossil fuel energy sources with renewable energy use will drive the carbon footprint in the region.

5. Conclusions and Policy Implications

Globally, environmental contamination has become one of the most talked-about topics. As a consequence of this, practically every country in the world is being pressured to enact and adopt new environmental regulations to help them achieve environmental sustainability without compromising economic development. It is of the utmost importance for developing countries as well as developing economies to significantly reduce their levels of pollution. This is due to the fact that the selected countries are anticipated to substantially contribute to global production and, as a result, are projected to be responsible for a substantial portion of the environmental damage that occurs around the globe. Expansion of clean technology, carbon pricing, and green energy infrastructure are the pillars of eco-friendly initiatives that help decrease environmental exposure. This study aimed to investigate the impact of non-renewable nuclear energy, technological innovation, renewable and non-renewable energy use, and natural resources on the carbon footprint. The area of the study includes the top six nuclear energy countries by consumption in the Asia Pacific region and the time duration is 2001 to 2019. Due to the possibility of cross-sectional dependence, the current study used an estimating method of the second generation. The cointegration results investigated a long-term relationship between the series, and the findings of the Westerlund cointegration test confirmed the cointegration relationship between the series. In addition, the estimated results of the FMOLS and PDOLS models examined that substituting nuclear power plants for those that rely on fossil fuels would considerably lessen the environmental shame associated with using nuclear energy since nuclear power plants produce almost no carbon emissions [9,21,22,42]. Moreover, the primary motivation behind scientific progress and environmental regulations in major nuclear energy-producing countries is the promotion of industrial growth, which comes at the expense of the environment by producing ambient environmental contamination [38]. Furthermore, it can be concluded that countries with a high rate of nuclear energy production may reduce their carbon footprint by switching to renewable energy sources such as nuclear energy, which is good for the environment [1]. Comparatively, renewable energy sources are both sustainable and abundant, and they help to lessen environmental degradation, while non-renewable energy sources such as fossil fuels are limited and unsustainable, and their intensive deployment contributes to climate change and global warming by increasing greenhouse gas (GHG) emissions. Further ecological decline due to carbon emissions may be slowed if we keep using fossil fuels as a source of energy [1,39,40]. Lastly, in countries that produce a lot of nuclear energy, extracting natural resources has negative effects on the environment. Therefore, we all win since natural resource exploitation has an immediate, positive impact on both economic growth and, by extension, environmental degradation [14,41].

Finally, the causality studies of Dumitrescu and Hurlin revealed a unidirectional relationship between nuclear energy and carbon footprint. In contrast, a bidirectional causal relationship was exposed between technical breakthroughs, renewable and non-renewable energy, and carbon-intensive natural resources. These findings suggest that these variables have a substantial impact on the carbon footprint of the leading nuclear energy-producing nations. According to these calculations, nuclear and other energy sources, as well as carbon pricing, might be used to further the decarbonization goal. In contrast, a lack of access to clean fuel and green technologies, as well as a small proportion of cleaner energy sources in the conventional energy mix, are expected to increase carbon reimbursement. As a result, the carbon footprint will be significantly affected by policy

orientations toward all these explanatory indicators. Despite these benefits, the production of radioactive wastes such as uranium mill tailings and used reactor fuel raises various medical risks associated with nuclear energy usage. For millions of years, these substances may be radioactive and harmful to human health. It may result in radiation sickness, heart problems, cataracts, several forms of cancer, and even death.

In light of this study's empirical findings, there are a number of policy-level recommendations that might help these nations advance their environmental and economic goals simultaneously. First, with regard to the significant role that nuclear energy plays, the findings of this study lend support to the argument that the consumption of nuclear energy can be utilized as an essential source of energy in the development of long-term environmental policies and energy sources that are capable of meeting the growing demands for energy all over the world. Increased investment in nuclear energy supply and fewer constraints on nuclear energy evaluation are two areas where businesses and governments might benefit from significant encouragement. Additionally, preliminary efforts should be made to develop and produce nuclear energy infrastructure. Promoting additional initiatives connected to Public–Private Partnerships (PPPs) and recognizing barriers to expanding investments in alternative and cleaner energy sources might also enable domestic private shareholders and investors to be more actively involved in the broad spectrum of cleaner energy movements. Concerns expressed by private investors regarding governance-related threats may increase the burden of revolution on national governments and politicians. We also found that the circumstances in each country that generates nuclear power are unique; thus, the Paris Agreement (PA) should leave room for nuclear power if enough countries want to use it, which would improve the efficiency and cost-effectiveness of their efforts to lessen the environmental pollution. Since nuclear power generation has such devastating long-term consequences for people and the environment, it necessitates stringent safety and security procedures. However, it is crucial to keep in mind that nuclear power production necessitates protection and safety controlling expenses to avoid any accident that may seriously hurt the environment and damage people. Therefore, policy decisions surrounding nuclear energy should be assessed carefully from a number of perspectives, including its value in reducing environmental pollution, as well as its prospective hazards.

Second, public policies must provide financial assistance for various technical innovation initiatives, particularly the development of associated technologies that can ensure complementarity between reduced high economic growth and pollution. Credit systems that favor the manufacturing sector in promoting improved nuclear resolutions should also put stock in technical progress as a means of gauging energy efficiency in order to encourage expanded nuclear resolves. In order to lessen the impact of the environmental effects of natural resource rent in these nations, it is also essential to increase the use of eco-friendly equipment. The authors believe that technical progress in both natural resources and nuclear energy produced promising outcomes, despite the fact that the literature may take into consideration a direct dynamic link between natural resource rent and environmental damages. Moreover, the governing bodies and policymakers of these nations must stimulate private industry initiatives for the development of improved nuclear energy solutions and, subsequently, environmental protection. This proposal will help these nations take the first step toward reaching SDGs 7, SDGs 8, SDGs 9, and SDGs 13.

Third, in order to reduce environmental pollution, governments and policymakers should implement regulatory tactics, increase energy modernization, and encourage investment in alternative energy resources. Cleaner energy use improves human well-being. The additional energy that is produced as a result of economic growth needs to be repurposed into more environmentally friendly energy sources, and the progression of technology ought to be mandated as a practical method for reducing one's carbon footprint. In order to reduce environmental issues, governing bodies and policymakers in these nations should implement energy conservation strategies that are both timely and efficient. This might be accomplished by introducing low-carbon, clean, and reduced non-renewable energy usage in these nations. Regarding energy conservation, it is recommended that renewable and

alternative energy sources be put into use to lessen reliance on aging power infrastructure and guarantee reliable supply in a few large-scale deployment areas. This should include the industrial, residential, and transportation sectors, among others. In addition, officials should publish guidelines about the pricing of renewable and cleaner energy to encourage companies and people to rapidly transition away from energy generated by fossil fuels and toward renewable and alternative sources of power.

Fourth, the governing bodies of these nations need to immediately begin deliberating on how to make the most of the positive environmental impact that can be caused by technological advances in order to promote the preservation of the natural atmosphere. Therefore, governments should make a significant effort to support technology initiatives and environmental improvement to encourage environmentally friendly policies.

Environmentally friendly technologies and technology policies have an obligation to guarantee that environmental and social problems may be addressed while simultaneously promoting environmentally and economically sustainable growth. In addition, it is essential to determine green and clean criteria for experts with the capacity to defend environmental excellence. The construction of a market podium by technological innovation enables businesses to profitably divide inventive technologies and remuneration while simultaneously establishing perceptive synergies. In addition, the benefits of sustainable economic growth will boost environmental awareness and educational administration policies.

The empirical analyses in this work were conducted at an aggregate level. This may be seen as the primary limitation of the research. A further disadvantage of the current research is its small sample size (only six nations) with the Asia Pacific region data (2001–2019). Future studies may be conducted on other samples and may include numerous additional nuclear energy-related parameters in order to investigate this association in depth. In the upcoming research, corruption, financial development indicators, governance, environmental-related technologies, human capital, institutional quality, income inequality, and poverty can all be included in this relationship. By using these metrics, policymakers may better safeguard environmental quality, foster economic growth, and promote a variety of other areas.

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