Received: 01 July 2024 | Revised: 25 August 2024 | Accepted: 10 September 2024
https://doi.org/10.56946/jeee.v3i2.448
Journal of Environmental and Energy Economics

Research Article

Dynamic Impacts of Sustainable Energies, Technological Innovation, Economic Growth, and Financial Globalization on Load Capacity Factor in the Top Nuclear Energy-Consuming Countries

Samanta Islam[1], Asif Raihan[2*], Arindrajit Paul[3], Mohammad Ridwan[4], Md. Shoaibur Rahman[5], Junaid Rahman[6], Tipon Tanchangya[6], Robeena Bibi[7], Sumaira[8], Abdullah Al Jubayed[9]

[1]Department of Environmental Science and Engineering, Jatiya Kabi Kazi Nazrul Islam University, Mymensingh 2220, Bangladesh
[2]Institute of Climate Change, National University of Malaysia, Bangi 43600, Selangor, Malaysia
[3]Department of Computer Science, University of Colorado Boulder, Boulder, CO 80309, United States
[4]Department of Economics, Noakhali Science and Technology University, Noakhali 3814, Bangladesh
[5]Department of Agroforestry and Environment, Hajee Mohammad Danesh Science and Technology University, Dinajpur 5200, Bangladesh
[6]Department of Finance, University of Chittagong, Chittagong 4331, Bangladesh.
[7]School of Public Administration, Hohai University, Nanjing, China.
[8]College of Economics and Management, Zhejiang Normal University, Zhejiang, China.
[9]Department of Economics, Western Kentucky University, KY 42101, United States.

*Corresponding author: asifraihan666@gmail.com, ORCID ID: 0000-0001-9757-9730

Abstract
Nuclear energy is often regarded as a very efficient method for promoting environmental sustainability. This study seeks to investigate the influence of nuclear energy, renewable energy, financial globalization, technical innovation, and economic expansion on the sustainability of the environment in the top 10 economies that consume nuclear energy. The research analyzed data from 1990 to 2020. The load capacity factor (LCF) serves as a novel indicator for ecological sustainability, elucidating the impact of human activities on ecological sustainability and the mechanisms by which nature mitigates human-induced harm. This study employed the Panel Dynamic Ordinary Least Squares (DOLS) method to analyze the dynamic effects of the variables being studied. The estimation results suggest that the use of nuclear and renewable energy, as well as financial globalization, contribute to environmental sustainability by raising the LCF. On the other hand, economic expansion and technological innovation negatively impact ecological sustainability as it decreases the LCF. The study suggests that the governments of the top 10 nations with the highest nuclear energy consumption should actively promote increased investment in green technology and renewable energy sources in order to attain environmental sustainability.

Keywords: Nuclear energy; renewable energy; load capacity factor; financial globalization; technological innovation; environmental sustainability

Introduction
Anthropogenic greenhouse gas (GHG) emissions from activities such as fossil fuel consumption, industrialization, production, deforestation, advancement, and population growth are causing global warming, which is currently one of the most urgent environmental concerns [1,2]. The ramifications encompass accelerated sea-level elevation, insecurity regarding food and water supplies, ocean acidification, severe droughts, heightened security vulnerabilities, biodiversity loss, disruption to agricultural operations, escalated healthcare expenses, and depletion of resources [3]. All of these factors have an impact on human existence, public health, ecological systems, societies, and economies. Disturbingly, the existing patterns of destruction indicate that the quantities of greenhouse gases may increase twofold compared to pre-industrial

times by 2035, which might result in a global temperature increase above 2°C. More than 70% of the emissions of greenhouse gases consist of carbon dioxide (CO_2), which leads to substantial harm to the environment. This situation has captured the interest of economists, ecologists, socioeconomic policymakers, and political authorities around the globe [4]. Although climate change has been acknowledged globally and there have been international agreements to tackle it, achieving environmental sustainability continues to be one of the most significant difficulties faced by humanity [5]. Researchers have focused substantially on studying environmental sustainability in relation to economic expansion in recent decades while giving less emphasis to the study of sustainability of the environment and financial globalization. Financial globalization offers sophisticated tools to strengthen the financial industry and promote sustainable development [6]. Nevertheless, the environmental consequences of financial globalization are only now being recognized from the standpoint of a green economy. The process of financial globalization has the potential to have a positive impact on the environment by reducing expenses and improving the allocation and utilization of resources. As a result, numerous countries currently give high importance to financial globalization in their approaches to development [7].

Prior research on financial development has shown inconsistent findings about the connection between ecological responsibility and financial globalization [8]. One viewpoint asserts that financial globalization has a positive effect on environmental sustainability by improving the affordability and availability of financial assets to overcome financial limitations. Consequently, this can facilitate the acceptance of eco-friendly technologies and the execution of more effective environmental strategies to reduce CO_2 emissions [9]. Nevertheless, the adoption of clean energy programs is hindered by many financial constraints, such as limited government support, severe banking laws, rising loan expenses, and restricted access to financing [10]. Financial globalization in this context is linked to the deterioration of the environment [11]. Furthermore, both theoretical and empirical investigations highlight the significance of technological innovation in achieving environmental sustainability and driving economic advancement. Previous research have shown that technology innovation has positive effects on reducing CO_2 emissions and improving environmental quality [12]. Furthermore, multiple empirical studies have shown a clear inverse relationship between the utilization of renewable energy and the degradation of the environment [13]. Nevertheless, it is important to highlight that nuclear energy has the ability to decrease CO_2 emissions and ecological expenses, emphasizing its promise as a viable and long-lasting energy source [14].

The impetus for undertaking this empirical investigation arises from the urgent necessity to comprehend the intricate interrelationships among sustainable energies, financial globalization, advances in technology, and ecological sustainability, specifically within the top 10 nations that consume nuclear energy (United States, France, China, Canada, Russia, Korea, Ukraine, Sweden, Spain, and Germany). These economies are experiencing tremendous growth and have become powerful drivers of global economic advancement, accounting for 57.72% of the world's GDP and 42.13% of world commerce in 2022 [15]. Nevertheless, they also play a significant role in causing environmental devastation, accounting for roughly 57.33% of worldwide CO_2 emissions in 2020 [15]. Furthermore, these economies have experienced remarkable economic growth by adopting financial globalization along with technological innovation, as evidenced by recent patterns in their economic advancement. Moreover, they have achieved significant advancements in promoting financial inclusion in the past twenty years by executing crucial measures to develop and improve their national financial inclusion programs, such as formulating objectives and implementing strategies. As a result, these economies have a very high global financial inclusion index. In 2021, the percentages of adults (age 15+) with interests in financial institutions were as follows: 94.95% in the United States, 88.71% in China, 99.98% in Germany, 99.63% in Canada, 98.67% in Korea, 89.72% in Russia, 99.24% in France, 99.69% in Sweden, 83.56% in Ukraine, and 98.30% in Spain [15].

The present study's objective is to investigate the dynamic impacts of nuclear energy, renewable energy, technological innovation, economic growth, and financial globalization on load capacity factors in the top nuclear energy-consuming countries. This research provides multiple contributions to the existing empirical literature. Firstly, it examines the impact of financial globalization on environmental sustainability in specific economies. Some scholars have analyzed the influence of the growth of the financial sector on environmental sustainability at different levels - regional, national, and global. Meanwhile, others have focused on assessing its effect on CO_2 emissions. Nevertheless, there is a limited amount of academic research that has investigated the impact of financial globalization on the sustainability of the environment. Moreover, these studies have reported conflicting results. Furthermore, this study is the initial empirical investigation that specifically analyzes the LCF among the top 10 nations that consume the most nuclear energy. The LCF denotes the proportion of real energy produced compared to the highest achievable output during a specific time frame. A value of 1 for the LCF indicates that the energy flow is equal to the maximum potential, which indicates optimal performance. If the LCF is below 1, it indicates that the actual output is lower than the maximum potential, which signals inefficiency or under utilization. On the other hand, if the LCF value is larger than 1, it means that the output is higher than the maximum possible value. This could indicate extraordinary efficiency or overloading. This research employs advanced econometric panel data estimate approaches, including Panel DOLS, to produce reliable findings and tackle frequent issues encountered in panel data analysis, distinguishing it from earlier empirical studies. The empirical findings will be beneficial for formulating effective policies towards sustainable development.

Literature Review

Several macroeconomic issues have been identified as having a direct or indirect impact on overall environmental quality. An analysis of the environmental consequences of economic expansion often revolves around the theoretical underpinnings of the Environmental Kuznets Curve (EKC) theory. This hypothesis posits that the relationship between economic expansion and the quality of the environment is characterized by a non-linear pattern, namely an inverted U-shape, as seen by reference [16]. The rationale behind the shape of the EKC is rooted in the impacts of economic growth on the environment, particularly in relation to the size, makeup, and technological advancements. The scale effect pertains to the adverse environmental repercussions that arise when economic growth stimulates economic activity. As a result, the need for energy and other variables that stimulate economic expansion typically rises, resulting in the emission of GHGs into the atmosphere. Furthermore, the concept of pollution havens and the race to the bottom idea suggest that financial globalization can instigate competition among states to lower their environmental standards. Hence, the objective of this research is to empirically examine these hypotheses in order to confirm or refute their validity.

Politicians worldwide have shown great interest in nuclear energy (NE) because of its significant potential to mitigate environmental degradation while ensuring economic growth [17]. Research has indicated a clear correlation between NE and the enhancement of environmental circumstances. Research has investigated the impact of NE on environmental deterioration in various economies, such as the SAARC economies [18], OECD nations [19], and specific countries including the USA, Japan, France, Russia, Ukraine, China, Spain, Canada, and the UK [20]. The findings indicate that NE has a positive impact on environmental quality. In contrast, alternative research has demonstrated either a lack of meaningful connection or a favorable association between the two factors. Research conducted on the US [21], a panel consisting of 30 nations [22], and the five countries with the greatest carbon emissions [23] has shown that NE plays a crucial role in regulating ecological footprint and has the capacity to ensure environmental sustainability. Hence, the absence of consistency in the results of many research provides an occasion to conduct a more comprehensive investigation into the impact of NE on LCF, specifically within the top 10 nations that consume the most nuclear energy.

Global policymakers are growing more worried about the dangers presented by worsening climate change [24] and are committed to developing and implementing policies to tackle this problem [25]. Prior research has recognized renewable energy (RE) as a pivotal element in enhancing environmental circumstances [26]. Scientists are becoming more interested in studying the correlation between RE and environmental sustainability. Caglar et al. [17] asserted that increased attention to RE has a substantial positive impact on the preservation of the environment in the EU nations. However, additional study emphasizes the crucial and immediate effects of energy obtained from fossil fuels on the long-term well-being of the environment [27-29]. Furthermore, Fang et al. [30] validated that RE is crucial in mitigating environmental harm. Furthermore, Li et al. [31] recorded a detrimental association between RE and CO_2 emissions in the BRICS countries. However, certain research have discovered just a small amount of evidence indicating that RE has a major impact on environmental contamination. As an illustration, Pata and Isik [32] conducted a comparison of the impacts of RE on LCF in the USA and Japan and did not observe any meaningful impact. Therefore, the discrepancies in results from different empirical investigations on the correlation between RE and LCF among the top 10 countries with the greatest nuclear energy consumption necessitate additional research.

Prior research has thoroughly examined the correlation between economic growth and ecological impacts [33,34]. The association between GDP and CO_2 emissions is generally recognized, as emissions tend to rise in tandem with the expansion of economic activity. However, the situation becomes more intricate when taking into account a wider ecological sustainability metric, such as the LCF, instead of only concentrating on CO_2 emissions. A study conducted by Raihan et al. [35] utilizing data from Mexico from 1965 to 2017 discovered a negative correlation between GDP and LCF. In a similar vein, Khan et al. [36] discovered a negative connection between GDP and LCF. Contrarily, 37. Akadiri et al. [37] discovered that while examining India, they first identified a positive correlation between GDP and LCF in the short-term, but saw a negative correlation in the long-term. In addition, Pata [38] conducted an empirical study utilizing the ARDL approach and discovered a negative association between GDP and LCF in Japan and the USA from 1982 to 2016. Furthermore, Pata and Isik [32] documented a detrimental effect of GDP on the LCF in China between 1981 and 2017. Hence, the contradictory results concerning the correlation between GDP and LCF across the top 10 nations with the highest nuclear energy consumption underscore the need for additional study to address this notable knowledge gap.

Both governments and academia are increasingly acknowledging the significance of technology in reducing environmental degradation caused by ongoing improvements in innovation [39]. TI has been the topic of comprehensive contemporary investigations, with multiple research endeavors specifically examining its environmental consequences [40]. These studies utilize various crucial indicators to evaluate the levels of information technology, such as efficiency, R&D, and developments in patents. However, a study conducted by Xu et al. [40] demonstrates that TI has a substantial impact in reducing the ecological footprint in big developing markets. However, their analysis also uncovers that TI can amplify CO_2 emissions in these particular circumstances. Prior research emphasizes the significance of TI in fostering ecological welfare. For instance, Sharif et al. [41] performed ARDL research on G7 countries and discovered that the utilization of innovative technology decreases environmental degradation. Raihan et al. [42] employed the DOLS approach and discovered a negative correlation between TI and pollution. Usman et al. [43] utilized the AMG technique to examine the influence of TI on the environment in Mercosur nations. Their findings demonstrate that technological advancement improves environmental quality. Therefore, it is necessary to examine the influence of technological innovation on long-term energy consumption patterns in the ten countries that consume the most nuclear energy.

Prior research has extensively examined the intricate connection between FG and LCF, revealing both positive and negative correlations between these concepts [44,45]. In the last ten years, several research have examined the connection between FG and LCF, producing conflicting findings. Adebayo et al. [46] used a quantile-based approach to analyze the relationship between FG and LCF in the G7 nations from 1990-2018. The results showed diverse outcomes, with a particularly beneficial impact observed in these countries. Moreover, Sharif et al. [41] conducted a reassessment of the influence of FG on ecological health in G7 countries spanning from 1995 to 2019. Their findings revealed a favorable correlation between FG and the promotion of a sustainable environment. Chen et al. [47] conducted a study utilizing the CS-ARDL approach to analyze the influence of FG on ecological efficiency across BRICS nations. The findings showed that FG had a negative impact on ecological footprints. Hence, it is imperative to examine the influence of FG on LCF in the top ten countries that consume the most nuclear energy.

The disparity in results may arise from the utilization of different econometric approaches, diversity in the choice of variables, nations, and time periods examined in the studies. The contrasting outcomes emphasize the necessity for additional research. An in-depth evaluation of empirical studies reveals substantial deficiencies in the existing empirical literature. Prior research has predominantly concentrated on the correlation between the economy and natural resources, often integrating renewable energy. Nevertheless, the significant impacts of RE, NE, TI, GDP, and FG on LCF have been conspicuously disregarded. In addition, a thorough analysis of the existing research reveals a lack of studies that particularly investigate these aspects in relation to the top 10 countries with the highest nuclear energy use. Thus, it is clear that the connections between RE, NE, TI, FG, GDP, and LCF have not been thoroughly investigated, despite their substantial influence on environmental sustainability. Thus, this study used the Panel DOLS technique to calculate the environmental impacts of the factors. This study emphasizes the need for additional analysis by examining the intricacies and inconclusive results of past studies. The findings help to settle existing arguments on the links among these variables.

Methodology

Empirical model and data

This study evaluates the influence of NE, RE, TI, GDP, and FG on LCF. The analysis specifically concentrates on the top 10 countries that consume nuclear energy, namely the United States, China, Russia, Canada, France, Spain, South Korea, Ukraine, Germany, and Sweden. The econometric model employed in this study is outlined as follows:

$$\mathrm{LCF_t} = \tau_0 + \tau_1\mathrm{GDP_t} + \tau_2\mathrm{RE_t} + \tau_3\mathrm{NE_t} + \tau_4\mathrm{TI_t} + \tau_5\mathrm{FG_t} + \varepsilon_t \quad (1)$$

Where, τ_0, τ_1, τ_2, τ_3, τ_4, and τ_5 are the intercept and coefficients of the variables whereas ε_t is the error term.
The variable LCF is determined by subtracting the ecological footprint from the biocapacity, allowing for the evaluation of a country's ecological sustainability in relation to a specific threshold. This technology enables comprehensive investigations of environmental degradation. It is essential to incorporate the LCF into environmental evaluation since it quantifies a country's capacity to sustain its population at existing living standards. In the past, the evaluation of environmental quality has mostly relied on CO_2 measures [48,49]. Furthermore, economic growth is evaluated based on the measure of GDP per capita. The correlation between economic growth and environmental degradation is significant, as previous global economies have tended to prioritize growth in the economy without fully considering the negative environmental consequences [50]. Nevertheless, there is currently an increasing global acknowledgment of the significance of environmental sustainability, resulting in significant endeavors to achieve a harmonious equilibrium between economic advancement and the preservation of the environment [16].
Additionally, the evaluation of RE and NE is based on the percentage of total energy use. In addition, TI is quantified by the overall quantity of patents, indicating a country's emphasis on advancing alternative energy sources like RE and NE, which are acknowledged for their reliability and environmental friendliness [51]. FG is a comprehensive term that includes the merging of financial sectors and organizations across different countries. Financial growth impacts the environment through different means, including promoting environmentally friendly efforts like programs for transitioning to renewable energy to fulfill the country's energy needs for industries and households, while also complying with environmental regulations [51]. Furthermore, the availability of funds provided through financial markets aids in the promotion and preservation of ecological conservation initiatives.

Table 1. Variables description and sources

Variables	Indicators	Unit	Source
LCF	Load capacity factor	Global hectares per capita	GFN
GDP	Gross domestic product	GDP per capita (current US$)	WDI
RE	Renewable energy	% of total energy use	WDI
NE	Nuclear energy	% of total energy use	WDI
TI	Technology innovation	Number of patents (residents, nonresidents)	WDI
FG	Financial globalization	Financial globalization index	KOF

Table 1 presents a concise overview of the data. The LCF data is obtained from the Global Footprint Network (GFN), while the data on FG is taken from the Swiss Economic Institute (KOF). The remaining data is obtained from the World Development Indicators (WDI). In order to ensure the coherence of the dataset, the variables are converted into their logarithmic form beforehand to do the analysis.

Unit root test

To prevent misleading regression results, it is necessary to employ a unit root test. The process involves checking the stationarity of variables in regression by taking differences and applying stationary methods to estimate the equation of concern. The empirical literature recognizes the need to establish the order of integration before examining the presence of cointegration among variables [52]. Multiple unit root tests should be used to assess the integration order of a series, as different unit root tests have varying effectiveness based on the size of the sample [53]. In order to identify the autoregressive unit root, this study employed three tests: the Augmented Dickey-Fuller (ADF) test [54], the Dickey-Fuller generalized least squares (DF-GLS) test [55], and the Phillips-Perron (P-P) test [56]. In this study, the unit root test was employed to verify that no variable surpassed the level of integration and to justify the application of the Panel DOLS approach instead of conventional cointegration methods.

Panel DOLS regression

The current study utilized the Panel DOLS [57], an expanded equation of ordinary least squares estimation, to examine the time series data. The Panel DOLS cointegration test includes explanatory factors and their initial difference terms, along with leads and lags, to control for endogeneity and generate standard deviations via a covariance matrix of errors that is robust against serial correlation [58]. The inclusion of the leads and lags of the different terms reveals that the error term is orthogonalized. The normal asymptotic distribution of the standard deviations of the Panel DOLS approximation allows for a credible examination of the statistically significant nature of the variables [59]. The Panel DOLS technique is useful for handling mixed orders of integration. It allows for the integration of individual variables in the cointegrated framework by measuring the dependent variable on explanatory factors in levels, leads, and lags [60].
The primary advantage of the Panel DOLS estimate is the use of mixed-order integration for each variable in the cointegrated framework. In Panel DOLS estimation, an I(1) variable was regressed against additional variables. Some of these variables were I(1) variables with leads (p) and lags (-p) of the first difference, whereas others were I(0) variables with a constant term. This estimate addresses limited sample bias, endogeneity, and autocorrelation concerns by aggregating the leads and lags across explanatory factors [61]. Therefore, once the stationarity of the variables has been verified, the study continues by doing Panel DOLS estimation to get the long-run coefficient. This is done using the equation provided below:

$$\begin{aligned}\Delta LCF_t = \tau_0 + \tau_1 LCF_{t-1} + \tau_2 GDP_{t-1} + \tau_3 RE_{t-1} ++ \tau_4 NE_{t-1} + \tau_5 TI_{t-1} + \tau_6 FG_{t-1} \\ + \sum_{i=1}^{q} \gamma_1 \Delta LCF_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta GDP_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta RE_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta NE_{t-i} \\ + \sum_{i=1}^{q} \gamma_5 \Delta TI_{t-i} + \varepsilon_t + \sum_{i=1}^{q} \gamma_6 \Delta FG_{t-i} + \varepsilon_t\end{aligned} \tag{4}$$

where Δ is the first difference operator and q is the optimum lag length.

Results and discussion

Prior to commencing any analysis of regression, it is imperative to meticulously examine the fundamental characteristics of the variables and their interconnections. Table 2 displays the results of the summary measurements between variables, together with the statistical values obtained from various normality tests. Skewness values around zero indicate that all the variables conform to a normal distribution. Moreover, the results suggest that all the series exhibit platykurtic distribution, as seen by their kurtosis values being below 3. Furthermore, the lower Jarque-Bera values and probability values exceeding 0.05 indicate that all variables exhibit normal distribution.

Table 2. Summary statistics of the variables

Variables	LCF	GDP	RE	NE	TI	FG
Mean	0.17	9.80	1.94	8.41	10.30	3.99
Median	0.18	10.32	1.91	8.64	10.46	4.02
Maximum	0.86	11.03	3.95	10.11	14.28	4.41
Minimum	-0.48	7.12	0.16	1.34	5.74	2.56
Std. Dev.	0.56	0.45	0.74	0.41	0.87	0.29
Skewness	-0.18	-0.19	-0.43	-0.25	-0.58	-0.29
Kurtosis	2.42	1.75	2.12	1.75	2.58	2.75
Jarque-Bera	3.29	2.66	3.07	2.53	2.49	2.89
Probability	0.12	0.28	0.13	0.36	0.33	0.17

Note: LCF = Load capacity factor, GDP = Gross domestic product, RE = Renewable energy, NE = Nuclear energy, TI = Technology innovation, FG = Financial globalization

The conclusions of the unit root testing are presented in Table 3. The ADF, DF-GLS, and P-P tests reliably demonstrate the statistically significant nature of the variables when they undergo a single differencing. Considering the data that show stationarity, it is recommended to utilize the Panel DOLS econometric methodology, which is capable of handling variables that are stationary in both their original form and their initial differences.

Table 3. Results of unit root tests

Logarithmic form of the variables		LCF	GDP	RE	NE	TI	FG
ADF	Log levels	-0.21	-0.51	-0.81	-0.13	-0.49	-0.29
	Log first difference	-6.42***	-4.71***	-4.44***	-4.17***	-6.39***	-4.21***
DF-GLS	Log levels	-0.76	-0.38	-0.72	-0.53	-0.51	-0.89
	Log first difference	-4.36***	-4.17***	-3.94***	-3.87***	-6.07***	-3.96***
P-P	Log levels	-0.19	-0.49	-0.83	-0.18	-0.42	-0.28
	Log first difference	-6.13***	-4.71***	-4.44***	-4.02***	-6.49***	-4.61***

Note: ADF = Augmented Dickey-Fuller test, DF-GLS = Dickey-Fuller generalized least squares test, P-P = Phillips-Perron test, LCF = Load capacity factor, GDP = Gross domestic product, RE = Renewable energy, NE = Nuclear energy, TI = Technology innovation, FG = Financial globalization, *** indicates significance at a 1% level.

Table 4 presents the empirical findings obtained from the Panel DOLS estimation on the enduring impacts of independent variables on LCF. The strongly negative coefficient of GDP suggests that a 1% growth in GDP would result in a 0.29% decrease in LCF over a prolonged period of time. In contrast, the coefficients of RE and NE show a clear positive relationship with LCF, indicating that a 1% rise in RE and NE would result in a corresponding improvement of 0.15% and 0.17% in LCF. Nevertheless, the very adverse coefficient of TI suggests that a 1% rise in TI would result in a long-term decrease of 0.08% in LCF. Ultimately, the notably favorable coefficient of FG suggests that a 1% augmentation in FG would enhance LCF by 0.21% over an extended period of time.

Furthermore, it is important to mention that the signs of the computed coefficients align with both theoretical expectations and empirical observations. The inquiry also included a range of diagnostic tests to evaluate the appropriateness of the estimated model. The R^2 and modified R^2 values indicate a strong fit of the computed regression model. This implies that the independent variables can explain 98 percent of the variability in the dependent variable's changes. Furthermore, the F-statistic exhibits a p-value of 0.00, which signifies that the linear relationship of the model is statistically significant. Furthermore, the root mean square error (RMSE) and mean absolute error (MAE) values are close to zero and positive, suggesting that the outputs of the Panel DOLS model closely align with the data.

Table 4. Results of the Panel DOLS estimation

Variables	Coefficient	Standard error	t-statistic	p-value
GDP	-0.29***	0.10	-2.91	0.00
RE	0.15***	0.04	3.80	0.00
NE	0.17***	0.06	2.72	0.00
TI	-0.08***	0.02	-3.46	0.00
FG	0.21***	0.05	3.98	0.00
C	0.99	0.88	1.13	0.12
R^2	0.98			
Adjusted R^2	0.98			
F-statistic	86.61			0.00
RMSE	0.03			
MAE	0.02			

Note: *** indicates significance at a 1% level, LCF = Load capacity factor, GDP = Gross domestic product, RE = Renewable energy, NE = Nuclear energy, TI = Technology innovation, FG = Financial globalization, RMSE = Root mean squared error, MAE = Mean absolute error

This study investigates the dynamic impacts of nuclear energy, renewable energy, technological innovation, economic growth, and financial globalization on load capacity factor in the top nuclear energy-consuming countries. Figure 1 presents the summary of the study findings.

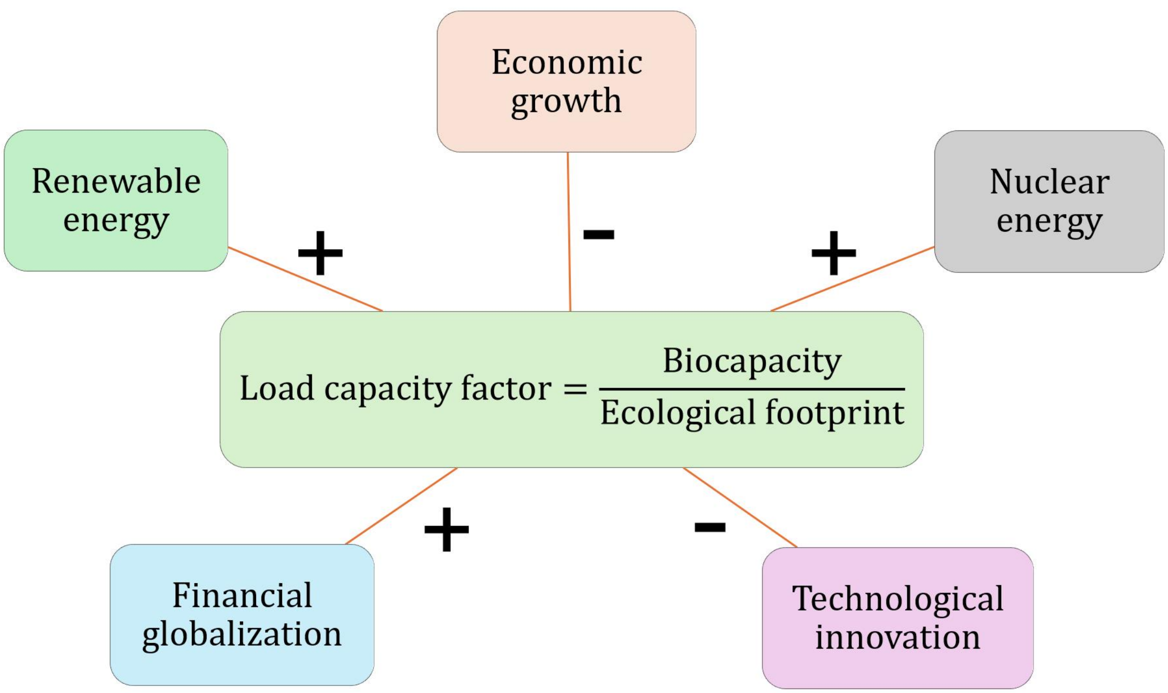

Figure 1. Summary of the study findings.

The findings of this study suggest that there is a negative correlation between GDP and LCF. The discovery aligns with prior research [35,36]. It is imperative for nations to adopt measures focused on mitigating the detrimental environmental impacts of economic expansion, which frequently arise from heightened reliance on polluting energy sources such as fossil fuels, resulting in raised levels of CO_2 and deterioration of ecosystems. Hence, it is recommended that governments of nations develop policies that give priority to the utilization of sustainable energies instead of fossil fuels in order to alleviate their environmental effects. By

embracing this strategy, these countries can achieve a harmonious equilibrium between environmental conservation and sustainable economic development.
In contrast, the results suggest a positive correlation between RE and LCF. Increasing the development and use of renewable energies in the top 10 nuclear power-consuming countries will improve environmental quality. The discovery aligns with prior investigations [25,26]. Similarly, the variable NE has a strong and statistically significant correlation with the variable LCF. The data suggest that the use of nuclear energy for industrial energy needs does not generate contaminants, hence avoiding environmental degradation. The results highlight the capacity of nuclear technologies to bolster energy security by decreasing reliance on fossil fuels and assuring stable prices while fostering ecological sustainability through a greater low-carbon footprint. It is advisable for the ten countries that consume the most nuclear energy to commence sustainable energy initiatives in order to uphold a harmonious equilibrium between economic advancement and environmental conservation. Furthermore, in light of the superior advantages of nuclear energy compared to renewable sources, it is imperative to enforce rigorous ecological rules and impose environmental levies in order to incentivize the shift from polluting to more environmentally friendly energy sources. Prioritizing awareness programs that emphasize the advantageous impact of nuclear energy in addressing climate change and improving quality of life is also crucial.
In addition, there is a negative association between TI and LCF. The discovery aligns with prior investigations [40]. The results can be ascribed to technical advancements, which frequently lead to heightened efficiency and output, potentially resulting in elevated energy usage and CO_2 emissions, thus generating an adverse environmental effect. Moreover, adopting new technology may require the gradual elimination of older, less effective systems, which could result in a temporary increase in CO_2 emissions. Nevertheless, the effect of innovation on the natural environment can demonstrate diminishing marginal returns, while the correlation is occasionally linear. The environmental impacts of innovation might differ depending on the nature of the invention and the specific operational circumstances in which it is implemented. Enhancing the efficiency of sustainable energies through the development of new technologies can aid in improving environmental quality, while the same cannot be said for fossil fuels. Hence, promoting green innovation is essential for attaining environmental quality objectives. Nevertheless, innovation in isolation is insufficient to have a beneficial effect on environmental quality without taking into account limitations on resources. In order to effectively tackle climate change vulnerabilities, it is crucial for sustainable environmental policies to have strong environmental legislation inside each country.
Ultimately, the results of the Panel DOLS analysis for FG indicate a favorable correlation with LCF. This implies that advocating for financial globalization can improve ecological norms in the top 10 countries that consume the most nuclear energy. The discovery aligns with prior research [41]. Financial globalization enables the expansion of foreign direct investment by implementing policies that promote freedom and openness. The findings suggest that increased financial globalization strengthens the adoption of ecologically sustainable practices by governments, local sectors, and global corporations. This technique offers a substantial amount of funding for the development of innovative and environmentally friendly technologies that are essential for enhancing energy efficiency. Furthermore, the process of financial globalization encourages increased investment in R&D, which in turn supports the development of environmentally friendly technology and ultimately contributes to ecological sustainability by enhancing the concept of life cycle assessment. Hence, it is advisable for the ten leading nations in nuclear energy consumption to strengthen financial globalization through the implementation of liberalization measures. This strategic maneuver can promote economic expansion while also achieving environmental sustainability objectives.

5. Conclusions and Policy Implications

Climate change is a pressing matter that requires our focus, as it impacts the quality of life and ecosystems through severe weather events, increasing sea levels, and the release of GHGs. This study aims to examine the correlation between renewable nuclear energies, economic growth, financial globalization, technological innovation, and environmental quality in the top 10 countries that consume nuclear energy. The LCF serves as an indicator of environmental quality in the chosen countries. This study utilized the Panel DOLS estimator to analyze time series data spanning from 1990 to 2020.

The findings of the Panel DOLS research reveal a strong negative impact of economic growth and technical innovation on ecological integrity in the top 10 nations that consume nuclear energy. This phenomenon may arise as a result of utilizing environmentally detrimental energy sources to fulfill the energy requirements of economic entities. Governmental entities are dedicating more R&D funds to green technologies as part of their efforts to promote technological innovation. In contrast, the analysis demonstrates that NE, RE, and FG have significantly positive effects on environmental quality. The effect of NE surpasses that of RE, and FG demonstrates a more significant impact than NE. Hence, it can be inferred that FG has the potential to exert a more significant impact compared to RE and NE.

This study presents policy recommendations for the top 10 economies that consume the most nuclear energy, based on the results of the Panel DOLS estimator. Initially, it is imperative for these nations to transition their energy supplies from environmentally harmful options to sustainable and eco-friendly alternatives. This transformation necessitates the reorganization of industries that presently depend on fossil fuels. In order to accomplish this, it is imperative to make ventures in nuclear energy as it is crucial for producing additional clean energy to meet the demands of both industries and households. The high energy density of nuclear energy enables the generation of large amounts of electricity using minimal nuclear fuel. Therefore, this shift in energy sources can improve effectiveness and decrease dependence on the extraction, transportation, and burning of fossil fuels, thus reducing environmental contaminants.

Furthermore, the necessary funding to expand and vary this structure can be obtained through the process of financial globalization. Foreign direct investment ought to be solely allocated to the development of new industrial facilities that prioritize energy efficiency. Foreign investors should be provided with incentives to encourage their investment in innovation and efficient energy sectors. Furthermore, it is imperative for financial institutions and politicians to offer substantial financial resources to support the industry. This includes providing green finance for investing in projects involving nuclear energy and allocating funds for R&D efforts focused on advancing breakthrough green technologies inside nuclear power systems.

Additionally, it is imperative for the top 10 nations that consume the most nuclear energy to give utmost importance to the development of environmentally friendly technologies. These nations must prioritize the allocation of funding for R&D in order to create green technologies, which provide substantial advantages for both economic expansion and environmental sustainability. These countries ought to provide financial support for environmentally friendly technology and promote the transition of stakeholders and industrialists from conventional industrial sectors to more sustainable and less polluting energy systems.

In addition, this study suggests that countries should allocate additional funding towards the development of advanced nuclear technology, including Generation IV reactors and small modular reactors. These technologies can enhance the management of nuclear waste by increasing efficiency and effectiveness, hence reducing environmental damage. Furthermore, it is imperative for governments to collaborate with the worldwide business community in order to secure funding for nuclear energy projects and stimulate advancements in technology. The cooperation will facilitate the advancement and implementation of efficient, sophisticated, contemporary, and impactful nuclear reactors to address the increasing need for clean energy across many industries.

Nevertheless, this research has specific constraints. The Panel DOLS model was employed for this inquiry rather than the Panel ARDL econometric framework. Future researchers have the option to employ either the Panel ARDL model or the CS-ARDL model for estimating coefficients, in addition to more sophisticated econometric methods. In addition, a dataset covering a period of 31 years, specifically from 1990 to 2020, was utilized for this investigation. The duration of the study may be prolonged until 2023, contingent upon the accessibility of data. Furthermore, this study specifically examines the top 10 countries that consume the most nuclear energy. Subsequent research can incorporate an additional panel dataset to do further analysis. Additionally, this research has the potential to be broadened by incorporating other possible factors, such as green technical advancement, investment in R&D, green finance, and economic intricacy.

Funding: This research received no funding.

Acknowledgment: Not applicable.
Conflict of Interest: The authors declare no conflict of interest.
Authors' contributions: Asif Raihan contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Asif Raihan, Samanta Islam, Arindrajit Paul, Mohammad Ridwan, Tipon Tanchangya, Junaid Rahman, Md. Shoaibur Rahman, Robeena Bibi, Sumaira, and Abdullah Al Jubayed. All authors read and approved the final manuscript.
Data availability statement: The data on the load capacity factor is obtained from the Global Footprint Network (https://www.footprintnetwork.org/), while the data on financial globalization is taken from the KOF Swiss Economic Institute (https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html). The data on economic growth, renewable energy, nuclear energy, and technological innovation are obtained from the World Development Indicators (https://databank.worldbank.org/source/world-development-indicators).

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