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Research Article

The Causal Effects of Nuclear Fusion Reactors, Human Development, and Economic Growth on Nuclear Energy Consumption in the United States

Mucahit Aydin [1,2,3] and Mehmet Aydin [1]

[1] *Faculty of Political Sciences, Department of Econometrics, Sakarya University, Esentepe Campus, Serdivan, Sakarya, Türkiye*
[2] *Research Methods Application Center of UNEC, Azerbaijan State University of Economics (UNEC), Baku AZ1001, Azerbaijan*
[3] *Sakarya University Technology Developing Zones Manager Company, 54050 Serdivan, Sakarya, Türkiye*

Correspondence should be addressed to Mucahit Aydin; aydinm@sakarya.edu.tr

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The study is aimed at investigating the effects of nuclear fusion reactors, human development, and economic growth on nuclear energy consumption in the United States from 1990 to 2019 using time and frequency causality analyses. The time domain causality analysis examined the relationship between variables over time using a single test statistic, while the frequency domain analysis explored causality in the short and long term at different frequencies. The findings from the time domain analysis indicated that nuclear energy consumption had a unidirectional causal effect on the human development index. Conversely, nuclear fusion reactors had a unidirectional causal impact on nuclear energy consumption. The results from the frequency domain analysis revealed that economic growth had a permanent unidirectional causal effect on nuclear energy consumption. In contrast, nuclear energy consumption had a temporary unidirectional causal impact on the human development index. Additionally, there was a bidirectional temporary and permanent causal effect between nuclear fusion reactors and nuclear energy consumption. Based on these findings, the study recommends that the United States continue providing financial incentives to develop nuclear energy technologies, such as constructing new nuclear power plants and offering subsidies to encourage the use of nuclear energy.

1. Introduction

Economic development is one of the most important indicators of a country's level of development. Development refers to an environment where improvements are experienced in the living standards of society, the organization of production, or the quality of goods produced [1]. Two approaches explain the level of economic development: income-based and human-based [2]. While the first approach measures development by per capita income, the second focuses on human development. The development was initially evaluated solely on economic facts, such as income, capital, and industrialization. This assessment included indicators such as human capital, education, and health in time. Whether H&D could be a substitute for EGRW in measuring economic development has raised interest in the possible relationship between these variables. H&D is defined as the process of enlarging people's choices to allow them to live healthier, fuller, and longer lives [3]. Recently, this process has been described as the ultimate goal of not only EGRW but also the development process [4]. H&D can be measured with the help of various indices. One of the most widely used, the H&D index published by the UNDP, is aimed at measuring the concept of development with a human focus. The main components that comprise the index are based on the standard of human living, healthy and long life, and access to information [5].

EGRW is defined as increased production over time and is one of the most important components necessary to ensure social welfare. H&D and EGRW are concepts that directly and indirectly affect each other. EGRW enables continuous improvements in areas such as education and health, while H&D contributes to economic growth, particularly in the workforce [6]. People are expected to contribute more to EGRW when they are healthier and more educated. Furthermore, EGRW is expected to promote H&D to the extent that countries with increased incomes can expand the choices and capabilities of decision-makers and households. Most studies on countries' development and welfare levels focus on economic development and the factors affecting it. In examining the literature, recent studies on factors that may be related to economic development indicate possible relationships between economic development and renewable-nonrenewable energy consumption. The relationship between ENC and economic development can be examined through H&D and EGRW, two variables representing economic development.

Energy is essential for countries' economic and social welfare, as it is one of the important production inputs necessary to ensure continuity in the production process. The increase in energy demand, with the Industrial Revolution and two major oil crises (1973 and 1979) that occurred at the end of the 20th century, further emphasized the importance of energy as a production input. Energy is closely related to production, economic growth, and human development. The importance and necessity of energy in terms of economic sustainability and development goals are indisputable. Energy sources, renewable and nonrenewable, appear in two forms. Just like nonrenewable energy, renewable energy affects human welfare.

Renewable energy sources can be replenished or regenerated over a relatively short period. This includes sources like solar, wind, hydropower, and geothermal. On the other hand, nonrenewable energy sources cannot be quickly replenished and are finite in supply. These include fossil fuels such as coal, oil, and natural gas. Nuclear energy is considered a nonrenewable energy source [7]. The fuel used in nuclear reactors, such as uranium and plutonium, cannot be quickly replenished and is finite in supply. Although the process of nuclear fission produces a large amount of energy, the fuel used in this process is not quickly replenished. Therefore, nuclear energy is not considered a renewable source of energy.

The relationship between nuclear energy and H&D is complex, with both positive and negative aspects to consider. On the positive side, nuclear power has been recognized as an efficient and reliable source of electricity and provides a steady flow of power necessary for developed societies. This has contributed to many countries' industrialization and higher economic development, with nuclear power playing an important role in powering factories, homes, and businesses. In addition to generating electricity, nuclear energy has also been used to support several medical and scientific advancements. For instance, nuclear technology has enabled scientists to explore the inner workings of the atom and develop new materials and technologies. In contrast, nuclear medicine uses radioactive isotopes to diagnose and treat diseases [8]. However, the use of nuclear energy also comes with significant challenges and risks. One of the biggest concerns is the potential for nuclear accidents, such as the disasters at Chernobyl and Fukushima, which have caused widespread damage and long-term health effects [9]. The management of nuclear waste represents a significant concern, given that it retains its radioactive properties for millennia, thereby presenting a plausible hazard to human health and the environment [10]. The countries' population growth and EGRW result in increased demand for electricity and other forms of energy. As societies industrialize and urbanize, the need for reliable and affordable electricity sources increases [11]. In recent years, nuclear power has proven to be a valuable option in meeting this demand, supplying a stable power source to meet this demand. Overall, nuclear energy is essential in providing clean, reliable, and versatile energy that can support the development and well-being of human societies [12, 13].

Another factor that is expected to impact nuclear energy is NFR. NFR is a type of nuclear power plant that uses the energy released from nuclear fusion reactions to generate electricity [14]. Nuclear energy, an important energy source used in electricity production by many of the world's countries, is produced using nuclear fission or nuclear fusion reactions and produces a huge amount of energy [14–16]. This energy helps to produce electricity by using it in power plants. NFR is a promising technology with the potential to provide clean, abundant, and safe energy for human societies [17]. While many challenges must be addressed, the potential of fusion reactors helps address some of the most pressing energy challenges the world may face today, revolutionizing how we generate and use electricity. As research and development in the field of fusion reactors continue, it will be important for countries to carefully consider the potential benefits and challenges of this technology and determine how it might affect existing energy systems. Moreover, one of the critical benefits of nuclear energy is its cleanliness [18]. Unlike fossil fuels, which release greenhouse gases and other pollutants when burned, nuclear power plants do not produce air or water pollution [19]. This makes nuclear energy a valuable tool in the fight against climate change, as it can help reduce carbon emissions and other pollutants that contribute to global warming. As shown in Figure 1, the United States is the second country after Europe for the cumulative CO_2 emissions avoided by global nuclear power.

Four hypotheses suggesting different energy policies on the relationship between EGRW and other types of ENC emerge in the literature; these are the growth, conservation, feedback, and neutrality hypotheses [21]. It is argued in the growth hypothesis that the direction of the relationship is from ENC to EGRW and that ENC contributes to growth as a complementary element of capital and labor. In the conservation hypothesis, the direction of the relationship is from EGRW to ENC, based on the idea that developments borne of EGRW affect ENC. The feedback hypothesis is predicated on the existence of a bidirectional relationship between ENC and economic growth. According to this hypothesis, ENC and EGRW are jointly determined and affect each other. The neutrality hypothesis posits that a negligible or nonexistent correlation between variables exists.

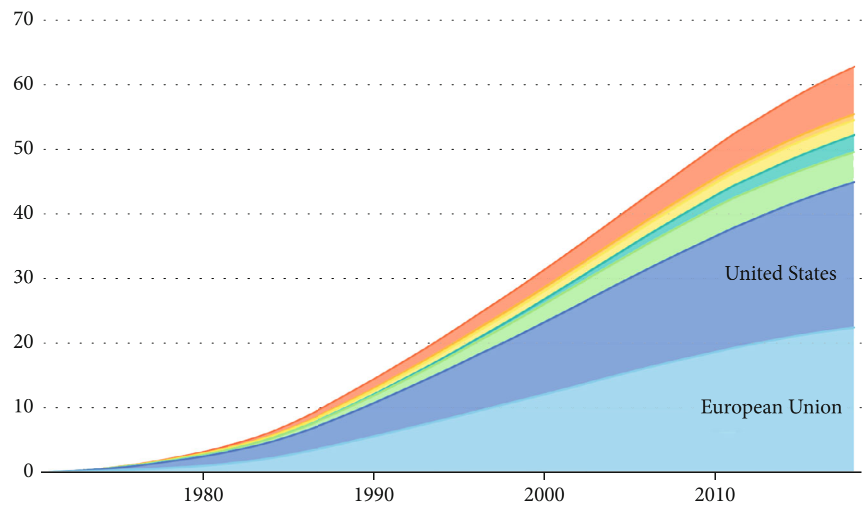

FIGURE 1: Cumulative CO_2 emissions avoided by global nuclear power in selected countries 1971-2018. Source: International Energy Agency [20].

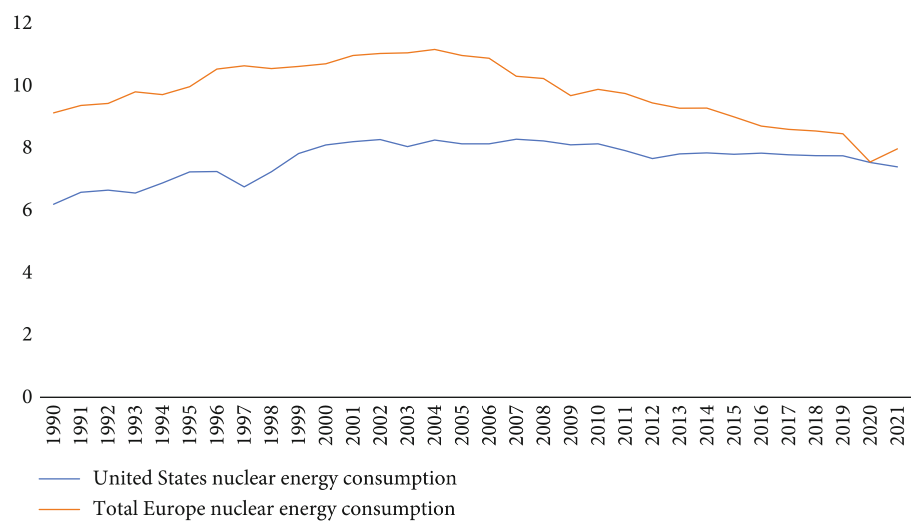

FIGURE 2: Total nuclear energy consumption in the United States and Europe in the period 1990-2021. Source: BP Statistical Review (2022).

According to the data of 2021 published in BP Statistical Review, the United States has the highest generation and consumption of nuclear energy. The share of nuclear in total annual electricity generation is 18.9%. It also has a long history of using nuclear energy and a large number of nuclear power plants. With all these features, the United States is a major player in the global nuclear energy market, and examining its NEC can provide valuable insights into the use of this energy source. Figure 2 shows the NEC in the US and Europe. As can be seen in Figure 2, the United States consumes nuclear energy close to almost all of Europe's consumption. Moreover, according to Figure 3, the number of patents for NFR in the United States is more than in Europe. The above information shows that selecting the United States was the right decision for the nuclear energy investigation.

Examining the relationship between ENC and H&D while considering the impact of energy on education, health, and communication reveals that the sophistication or lack of energy services is essential for human welfare. Energy is directly linked to the social, economic, and environmental dimensions, constituting integral components of sustainable development [22]. According to the World Energy Council, providing accessibility to energy is one of the most critical components of sustainable development. In countries where energy has a significant role in facilitating human life, human welfare is expected to be high regarding health and education. In contrast, in countries where it is smaller, human welfare is expected to be lower [23].

In this study, the causal effects of NFR, H&D, and EGRW on NEC were examined for the United States for the period 1990–2019 using time and frequency causality analyses. This study deviates from existing literature in several aspects: (i) This study represents the inaugural attempt to scrutinize the causal effects of NFR, H&D, and EGRW on NEC. NFR is a promising technology with the potential to provide clean, abundant, and safe energy for human societies [17]. Recently, R&D activities on nuclear energy, especially in the USA, have been accelerated. However,

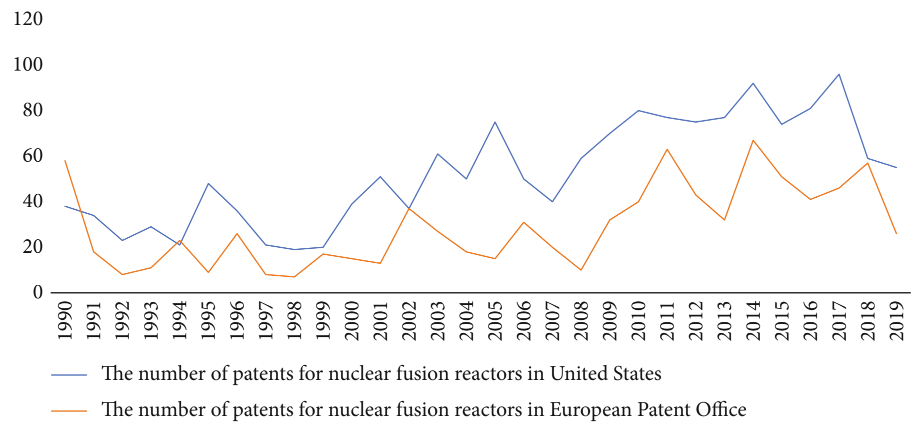

Figure 3: Number of patents for NFR in the United States and European Patent Office for the period 1990-2019. Source: OECD Statistics (2022).

examining the relationship between this energy source and H&D is essential for new research. This study will also guide future studies in this context. (ii) Frequency domain causality tests analyze several frequency points, whereas time domain causality tests only perform analysis at a time zero point. Hence, using frequency domain methodologies is essential for ensuring the robustness of results. In contrast to prior investigations that explored causality in the time domain, this study focuses on examining causality within the frequency domain, encompassing both short-term and long-run perspectives. (iii) The results of this study will guide policymakers on nuclear energy, which has become an increasingly important energy source today.

The second section of this study delves into an extensive examination of the existing literature, followed by a thorough elucidation of the empirical methodology in the subsequent section. The fourth section encompasses the presentation of empirical findings. The fifth and final section encapsulates the study's conclusions and provides pertinent policy recommendations.

2. Literature Review

This section provides a detailed literature review of the effect of NFR, H&D, and EGRW on NENC.

In the literature, many researchers have been investigating the effects of H&D on renewable and nonrenewable energy consumption. In these studies, it is seen that there is a complex and dynamic relationship between renewable and nonrenewable ENC and human development. According to Sasmaz et al. [24] for 28 OECD countries, Wang et al. [25] for BRICS countries, and Hashemizadeh et al. [26] for G-7 countries, renewable energy positively affects human development. There is a bidirectional relationship between these variables. At the same time, Wang et al. [27] concluded that renewable ENC in Pakistan does not improve human development, and increased economic income lowers human development. Similarly, in studies investigating the relationship between nonrenewable ENC and human development, the results vary at different development levels. Through correlation analysis, Martinez and Ebenhack [28] concluded that in countries where energy development is low, H&D significantly increases due to ENC; a moderate increase occurs in transition countries, and ENC in modern energy-consuming countries has no effect on human development. Steinberger and Roberts [29] found that attaining high human development and well-being at moderate levels of environmental pressure and resource use is possible. However, exceeding these levels may not necessarily result in further improvements in living standards. Van Tran et al. [30] conducted a study on the influence of ENC on H&D in 93 nations between 1990 and 2014. The research findings suggest that ENC has no impact on H&D. Hashemizadeh et al. [26] showed a bidirectional causal relationship between H&D and ENC using econometric tests for the period 1990-2015 in G-7 countries. Kaewnern et al. [31] conclude that renewable ENC positively impacts H&D in the top ten countries regarding H&D. Furthermore, the research identifies a unidirectional causal relationship from H&D to REN. Although many studies exist in the literature on the relationship between renewable and nonrenewable ENC and human development, very few studies examine the relationship between nuclear energy and human development. Sadiq et al. [32] examined the impact of financial globalization, nuclear energy, and external debt on the environment and H&D of the BRICS countries. According to the results, nuclear energy contributes to human development, and there is bidirectional feedback causality between H&D and NEC. Sadiq et al. [33], in a heterogeneous panel of 16 OECD countries for the period 1990-2019, investigated the effects of nuclear energy, public debt, and commercial globalization on H&D and concluded that nuclear energy boosts human development. The results also show a bidirectional feedback causality between NEC and human development.

In the studies investigating the relationship between EGRW and NEC in the United States, it is seen that different hypotheses about the direction of the relationship between these variables are supported according to the data period and the methods used. Payne and Taylor [34] revealed that there is no relationship between the increase in NEC and real GDP growth for the United States in the 1957-2006 period with the Toda and Yamamoto [35] causality test, while Wolde-Rufael and Menyah [36], using the causality

Table 1: Descriptions of variables.

Variable	*Indicator*	*Measure*	*Source*
Growth	GDP	Constant 2015 US$	World Bank [46]
Nuclear energy consumption	NEC	Million tonnes of oil equivalent (Mtoe)	BP [47]
Human development index	HDI	Index	Human Development Report [48]
Nuclear fusion reactors	NFR	The quantity of patents for nuclear fusion reactors	OECD [49]

Source: authors.

test Toda and Yamamoto [35], revealed that there is a bidirectional causal relationship between EGRW and NEC in the United States in the 1971-2005 period. Similarly, Omri et al. [37] found a bidirectional causal relationship between EGRW and NEC in the United States. Lee and Chiu [38] used the Toda and Yamamoto [35] causality test to examine the relationship between NEC and economic growth in the United States from 1965 to 2008. In 1990-2013, Saidi and Mbarek [39] utilized the panel Granger causality test to investigate the same relationship. Meanwhile, Chang et al. [40] employed the panel Granger causality test to examine the relationship between NEC and economic growth in the United States from 1971 to 2011. Lastly, Menyah and Wolde-Rufael [41] used a modified version of the Granger causality test to investigate the relationship between NEC and economic growth in the United States from 1960 to 2007. All four studies concluded no causal relationship between NEC and economic growth in the United States. Ozcan and Ari [42] investigated the causal relationship between NEC and EGRW for 15 OECD countries, including the United States, using the Hacker and Hatemi-J [43] bootstrap causality test in 1980-2012. The findings indicate a one-way causal connection from EGRW to NEC in the US. Meanwhile, in Belgium, Soytas et al. [44] utilized a multivariate model to explore the correlation between economic growth, nuclear and renewable energy usage, CO_2 emissions, and total primary energy supply from 1974 to 2019. According to the results, phasing out nuclear power should be managed by gradually commissioning renewable energy capacity. Magazzino et al. [45] examined the relationship between NEC and EGRW in Switzerland from 1970 to 2018, using the series approach and machine learning methodology. There is evidence to suggest that there is a one-way causal relationship between NEC and economic growth.

To the author's knowledge, no empirical study in the literature investigates the correlation between NEC and NFR. This study is aimed at filling this gap in the literature. In addition, it seems that no study in the United States examines the causality between H&D and NEC. In this respect, it is expected to contribute to the literature. Finally, this study is aimed at contributing to the literature in determining the impact of NFR, human development, and EGRW on NEC in the United States in both time and frequency domains.

3. Data and Methodology

3.1. Data. This study examined the causal effects of NFR, human development, and EGRW on NEC in the United States from 1990 to 2019. Table 1 provides a summary of information about the variables. Also, we took the logarithms of the variables. Table 2 and Figure 4 show the variables' descriptive statistics and time graphs, respectively.

Table 2: Descriptive statistics of the variables.

	HDI	*GDP*	*NEC*	*NFR*
Mean	0.900	1.48*E*+13	7.648	52.900
Maximum	0.930	1.99*E*+13	8.291	96
Minimum	0.872	9.80*E*+12	6.202	19
Std. dev.	0.016	3.06*E*+12	0.607	22.882
CV	1.777	20.675	7.936	43.255

Note: CV indicates the coefficient of variation.

3.2. Methodology

3.2.1. Fourier ADF Unit Root Test. Enders and Lee [50] modified the ADF test by incorporating Fourier terms to facilitate the detection of smooth structural breaks. In their approach, Enders and Lee [50] considered structural breaks using the deterministic term, which is defined as the following:

$$a(t) = a_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right). \quad (1)$$

The suggested FADF test model involves the use of k, which represents the frequency number of Fourier terms [50]:

$$\Delta y_t = a_1 + \delta t + \beta y_{t-1} + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^{p} \vartheta_i \Delta y_{t-\mathrm{i}} + u_t. \quad (2)$$

Enders and Lee [50] suggest a two-step approach for executing the FADF unit root test. The first step involves estimating the model between $1 \leq k \leq 5$ and selecting the best-fitted model based on the lowest sum of squared residuals (SSR). In the second step, the significance of the Fourier terms is determined using the conventional F test. If the Fourier terms turn out to be significant, the FADF test is employed to verify the null hypothesis. If the Fourier terms are insignificant, the ADF unit root test is conducted.

3.2.2. Fourier Toda-Yamamoto Causality Test. It is crucial to determine the highest level of series integration (dmax) and the appropriate length of the VAR model's lag (p) to conduct

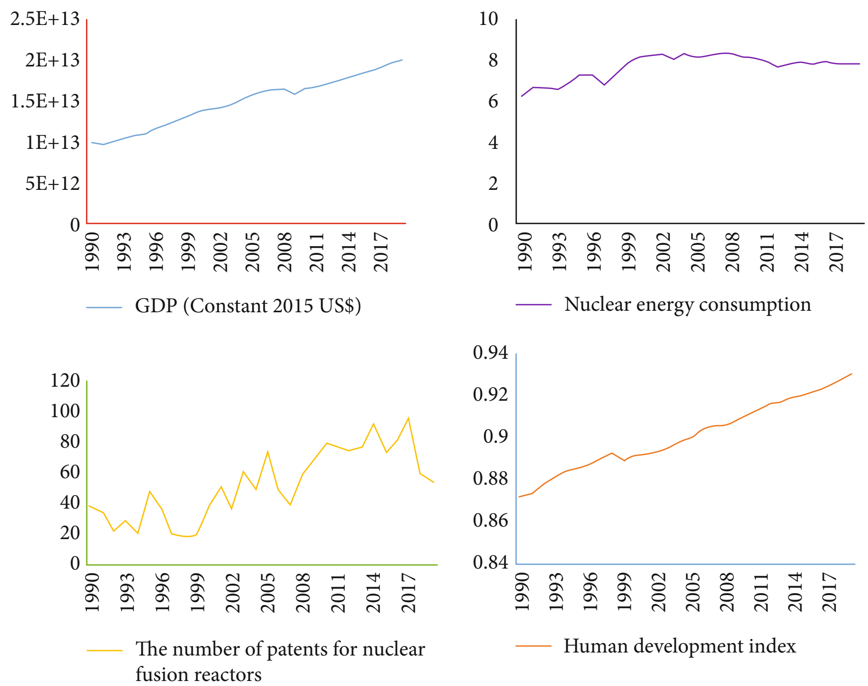

Figure 4: Graphs of the variables in the period 1990-2019.

the TY (1995) causality test effectively. The VAR model is calculated with the lag length (p + dmax), and the TY causality test is conducted accordingly. However, it is important to note that the TY causality test does not account for structural breaks, meaning that it may produce biased outcomes when applied to series analyses with structural breaks. To address this issue, Nazlioglu et al. [51] incorporated the deterministic term:

$$a(t) = a_0 + \gamma_1 \sin\left(\frac{2\pi \text{kt}}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right). \quad (3)$$

The deterministic term has k frequencies and is a function of time. Using this deterministic term, Nazlioglu et al. [51] enhanced the TY methodology and suggested the following model:

$$y_t = a_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \cdots + \beta_{p+\text{dmax}} y_{t-(p+\text{dmax})} + \varepsilon_t. \quad (4)$$

The frequency length is denoted by k in the Fourier TY causality test. The test's null hypothesis suggests no causal relationship between the variables. On the other hand, the alternative hypothesis shows causality.

3.2.3. Frequency Domain Causality Test. Frequency domain causality tests concentrate on assessing correlations between variables at different frequencies over time, contrasting with time domain causality tests that scrutinize relationships between variables using a single test statistic across time. In contrast to conventional causality tests, frequency domain causality testing delves into causal links by allowing the segmentation of the entire period into short, intermediate, and long intervals. Moreover, employing a spectral density function, frequency causality analysis can detect periodic variations in series, offering a more thorough comprehension of the events under investigation than time domain analysis. Therefore, it can provide more comprehensive information to policymakers (many studies in the literature have used frequency domain causality analysis [52–63]). Granger [64] initially proposed the causality analysis, later refined by Geweke [65] for the frequency domain. The methodology was further developed by Hosoya [66] and Breitung and Candelon [67]. Breitung and Candelon [67] expanded the Geweke [65] approach to bivariate VAR models. The following is a definition of a finite-order VAR model for frequency domain causality testing:

$$z_t = [x_t, y_t]'. \quad (5)$$

The lag operator (L) can be used to represent this model as follows:

$$\Theta(L) z_t = \varepsilon_t, \quad (6)$$

where $\Theta(\text{L}) = I - \Theta_1 \text{L} - \Theta_2 \text{L}^2 - \cdots - \Theta_p \text{L}^p$ (2×2 lag polynomial), $L^k z_t = z_{t-k}$, and ε is the error vector that represents white noise.

Using the Cholesky decomposition, the VAR model can be written as follows as a moving average model.

$$\begin{aligned}(z_t) = \Phi(L)\varepsilon_t &= \begin{pmatrix} \Phi_{11}(L) & \Phi_{12}(L) \\ \Phi_{21}(L) & \Phi_{22}(L) \end{pmatrix} \begin{pmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{pmatrix} \\ &= \psi(\text{L})\eta_t = \begin{pmatrix} \psi_{11}(L) & \psi_{12}(L) \\ \psi_{21}(L) & \psi_{22}(L) \end{pmatrix} \begin{pmatrix} \eta_{1t} \\ \eta_{2t} \end{pmatrix},\end{aligned} \quad (7)$$

Table 3: Unit root test results.

Variables	FADF Level $I(0)$	k	p	ADF Level $I(0)$	First difference $I(1)$	$p\ I(0)/I(1)$
lnNEC	-3.477	1	3	-1.801	-5.045*	0/0
lnGDP	-3.502	1	3	-2.064	-4.196**	1/0
lnNFR	-3.515	1	3	-3.461***	—	0
lnHDI	-3.284	1	3	-2.458	-5.721*	0/0

Notes: $^{*}p < 0.01$, $^{**}p < 0.05$, and $^{***}p < 0.10$. Optimal frequency and lag are represented by k and p, respectively.

Table 4: Fourier Toda-Yamamoto causality test results.

Causality	Values	Prob.	k	p
lnNEC⟶lnGDP	0.676	0.707	1	2
lnGDP⟶lnNEC	3.269	0.195	1	2
lnNEC⟶lnHDI	25.839*	0.002	2	2
lnHDI⟶lnNEC	3.493	0.342	2	3
lnNEC⟶lnNFR	6.948	0.128	1	3
lnNFR⟶lnNEC	7.989***	0.082	1	3

Note: $^{*}p < 0.01$ and $^{***}p < 0.10$.

Table 5: Frequency domain causality results.

Directions	$w = 0.5$ *(permanent)*	$w = 2.5$ *(temporary)*	10%
lnNEC⟶lnGDP	0.001	0.012	0.194
lnGDP⟶lnNEC	0.225*	0.017	0.156
lnNEC⟶lnHDI	0.104	0.582*	0.105
lnHDI⟶lnNEC	0.016	0.025	0.216
lnNEC⟶lnNFR	0.089*	0.091*	0.086
lnNFR⟶lnNEC	0.402*	0.108*	0.095

Note: $^{*}p < 0.10$.

where $\Phi(L) = \Theta(L)^{-1}$, $\psi(\mathrm{L}) = \Phi(\mathrm{L})^{-1}G^{-1}$, $E(\eta_t \eta_t{}') = I$, and $\eta_t = G\varepsilon_t$. G stands for the lower triangular matrix. Based on these equations, the spectral density of X_t can be shown as follows:

$$f_x(\omega) = \frac{1}{2\pi}\left\{\left|\psi_{11}\left(e^{-i\omega}\right)\right|^2 + \left|\psi_{12}\left(e^{-i\omega}\right)\right|^2\right\}. \tag{8}$$

Therefore, the definition of the Geweke [65] proposed measurement of causality is as follows:

$$M_{X\longrightarrow Y}(\omega) = \log\left[1 + \frac{\left|\psi_{12}\left(e^{-i\omega}\right)\right|^2}{\left|\psi_{11}\left(e^{-i\omega}\right)\right|^2}\right]. \tag{9}$$

Under the condition that the above equation equals zero, y does not cause x at frequency ω. Breitung and Candelon [67] approach is based on the following linear constraints.

$$\begin{aligned} &\sum_{j=1}^{p}\theta_{12j}\cos(j\omega) = 0, \\ &\sum_{j=1}^{p}\theta_{12j}\sin(j\omega) = 0, \end{aligned} \tag{10}$$

where θ_{12j} is the (1, 2) element of Θ_j. Croux and Reusens [68] use the incremental R-squared to test the null hypothesis that there is no Granger causality at the given frequency.

4. Empirical Results and Discussions

We utilized the Fourier-based unit root test to examine the stationarity of the variables. The outcomes of the unit root test are presented in Table 3. According to the results, all variables except lnNFR have a unit root at level, while stationarity is their first difference. On the other hand, the lnNFR is stationary at this level. We used the ADF results because the Fourier terms in the FADF model were insignificant. Accordingly, all variables except lnNFR are $I(1)$, while lnNFR is $I(0)$.

As part of our empirical analysis, we examined the causal relationship between lnNEC and lnHDI, lnGDP, and lnNFR. This was accomplished by utilizing two distinct causality methodologies, each exploring causality from different perspectives: time and frequency domain causality. Table 4 shows Fourier TY causality test results, a time domain causality test. The results show unidirectional causality from lnNEC to the lnHDI. Furthermore, the direction of causality is from lnNFR to lnNEC.

Table 5 indicates the frequency domain causality test results. Temporary and permanent represent short- and long-run causality, respectively. The causality test results in the frequency domain can be summarized as follows: (1) lnGDP has a permanent unidirectional causality towards lnNEC; (2) lnNEC has a temporary unidirectional causality towards lnHDI; and (3) lnNFR and lnNEC have a bidirectional causality, both temporary and permanent.

The results of the frequency domain causality analysis are reported in Figure 5. The results of this study should be considered, given certain constraints. This investigation centers on elucidating the causal effects of lnNFR, lnHDI, and lnGDP on lnNEC in the US. The US stands as one of the foremost nations in NEC and innovation. Consequently, the outcomes derived for the US may lack generalizability to other nations. Furthermore, given the study's focus on causality, it does not furnish insights into the magnitude of relationships between the variables under examination. Considering these limitations, long-term relationships can

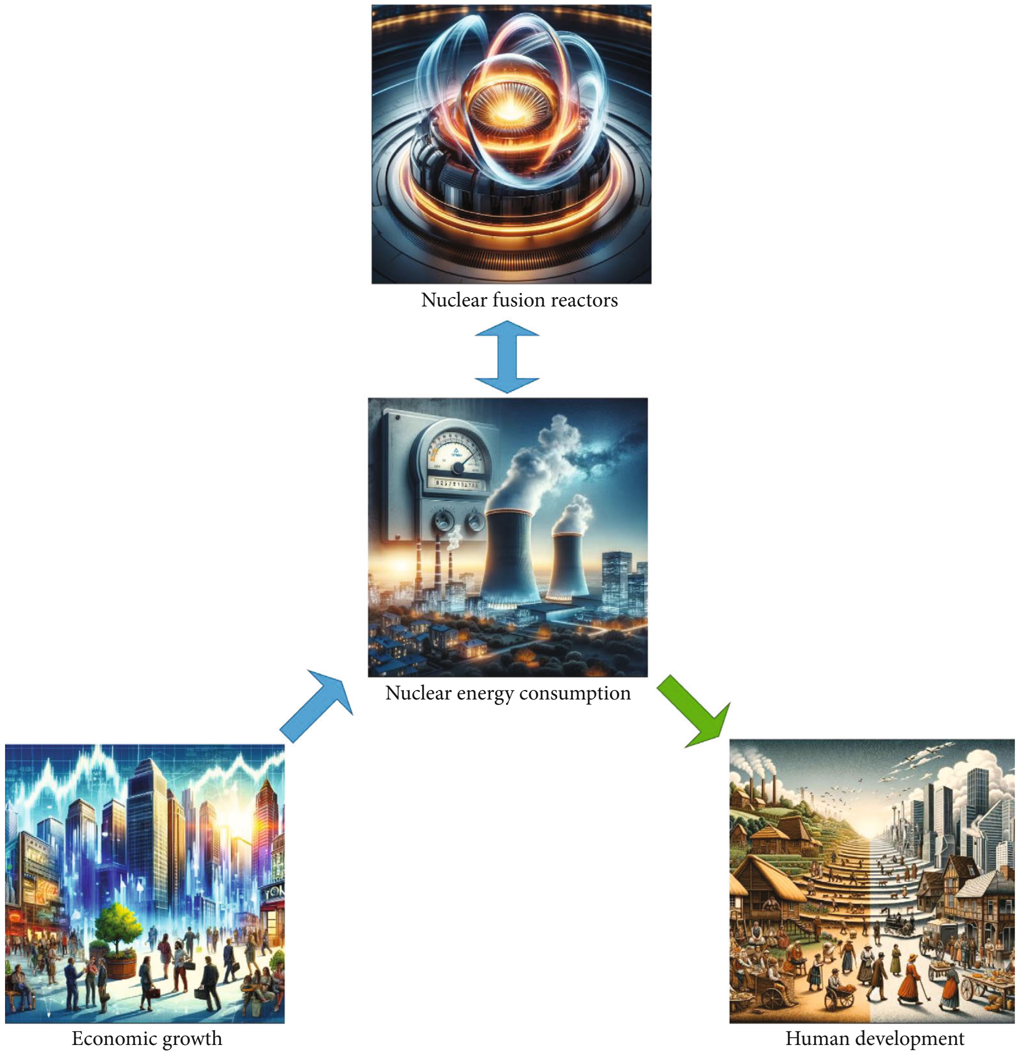

Figure 5: Graphical results of the frequency domain causality analysis. Note: blue and green arrows represent permanent and temporary causality, respectively.

be investigated under an economic model for different country groups, such as country groups with high or low lnNEC, in future studies.

5. Conclusions and Policy Recommendations

This study investigated the causal effects of NFR, human development, and EGRW on NEC in the United States for the period 1990–2019 using time and frequency domain causality analyses. In the study, firstly, the stationarity levels of the series were determined by ADF and Fourier ADF unit root tests. Unit root test results indicate that all variables except NFR have a unit root at a level, while stationarity is their first difference. On the other hand, NFR is stationary at the level. Then, the causal relations between NEC and H&D index, economic growth, and NFR were examined using two distinct causality methodologies to make comparisons.

Time domain analysis results can be interpreted as follows: (i) unidirectional causality exists from NEC to the H&D index and (ii) the direction of the causality is from NFR to NEC. These outcomes contrast with the results in Table 5, suggesting the superior effectiveness of the frequency domain analysis. Discrepancies observed in the outcomes of the two analyses indicate that the frequency domain causality analysis reveals causal connections not identified in the time domain analysis. For instance, the anticipated mutual relationship between NEC and NFR, undetected in the time domain, was established through the frequency domain analysis. The study's outcomes were scrutinized separately regarding both time and frequency domains. The interpretations of frequency domain findings are as follows:

For instance, the anticipated reciprocal relationship between NEC and NFR, undetected in the time domain, was established through the frequency domain analysis. The study's outcomes were scrutinized separately regarding both time and frequency domains. The interpretations of frequency domain results are as follows.

(1) Unidirectional permanent causality exists from EGRW to NEC. This result makes the conservation

hypothesis valid in the United States. Therefore, the developments borne of EGRW affect NEC. According to this result, EGRW policies in the USA will also affect NEC. These effects are expected to be positive. Therefore, if the US wants to expand the use of nuclear energy, it may be beneficial for them to follow a policy that encourages economic growth. Also, results could be interpreted as the economy expands; there is an increased demand for energy, including nuclear energy, to support economic activities in the long run. In this direction, policymakers can focus on strategies that promote EGRW to support the expansion of NEC. Policies that foster economic development, such as investment in infrastructure, technological innovation, and industrial expansion, could indirectly contribute to increase NEC. Finally, the results of unidirectional causality from EGRW to NEC in the United States support the findings of Ozcan and Ari [42]

(2) There is unidirectional temporary causality from NEC to the H&D index. The main reason is that the United States is actively implementing energy policies. The possible effects of NEC on H&D in these countries can be explained by the effective use of NEC in terms of education, health, and economic sustainability. It may be beneficial for the H&D of policymakers not to ignore the effects it may have on H&D while determining nuclear energy policies. In this context, the use of nuclear energy and developments in this field are expected to affect H&D positively. It may be beneficial for the H&D of policymakers not to ignore the effects it may have on H&D while determining nuclear energy policies. Also, policymakers should consider the temporary nature of the relationship when formulating policies related to nuclear energy and human development. While nuclear energy may contribute to short-run improvements in specific areas of human development, a comprehensive approach should be adopted to address broader factors that drive sustainable and long-term progress in human development. It is seen that the causality between NEC and H&D in the United States differs from the results in the literature in terms of the direction of causality. Sadiq et al. [33] and Sadiq et al. [32] found a bidirectional causal relationship between NEC and H&D for the BRICS and 16 OECD countries, respectively, while in this study, temporary unidirectional causality from NEC to H&D was reached for the United States. This difference can be explained by the fact that the United States of America has high H&D and NEC compared to other countries

(3) The existence of a bidirectional causality relationship between NFR and NEC may mean that there is a mutually reinforcing relationship between the two variables. As nuclear fusion technology progresses and becomes more viable, NEC may increase as fusion reactors are incorporated into the energy infrastructure. Simultaneously, higher demand for nuclear energy can spur investments and advancements in nuclear fusion research and development. Furthermore, the results imply that advances in fusion technology may play a role in meeting the energy demands of the future. As nuclear fusion technology matures and becomes commercially viable, it has the potential to contribute significantly to overall nuclear power generation and consumption in the United States. Two critical issues to consider with NEC are the cost of nuclear energy compared to other power sources and public opinion. In most cases, nuclear power is more expensive than other forms of energy. Also, nuclear energy is controversial in many countries, and there is often strong opposition. This can make building new nuclear power plants difficult, even if they are considered a good, clean, and reliable energy source. Policymakers can provide financial incentives for developing nuclear energy technologies, such as the construction of new nuclear power plants and subsidies to encourage the use of nuclear energy. It can also increase investment in research and development to improve the safety and efficiency of nuclear power generation. This could help lower the costs of nuclear power and make it more competitive with other forms of energy. Overall, these results may provide useful information for policymakers of the United States to shape effective policies on growth, human development, and nuclear energy

Abbreviations

EGRW: Economic growth
ENC: Energy consumption
NEC: Nuclear energy consumption
NFR: Nuclear fusion reactors
H&D: Human development
ADF: Augmented Dickey-Fuller
UNDP: United Nations Development Programme
REN: Renewable energy consumption
VAR: Vector autoregressive
TY: Toda and Yamamoto
US: United States
FADF: Fourier ADF.

Data Availability

Data is available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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