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Impact of Nuclear Energy Consumption on CO_2 Emissions in South Korea: Evidence from Fourier Bootstrap ARDL Bound Test

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ABSTRACT

A global trend of rising non-renewable energy consumption is associated with an increase in CO_2 emissions and a consequent acceleration of global warming. To mitigate global warming, there is a growing need for consumption based on renewable energy sources and nuclear energy. The Republic of Korea – South Korea has emerged as a global leader in both the production and consumption of nuclear power. This study examines the impact of nuclear energy consumption on CO_2 emissions in South Korea within the framework of the Environmental Kuznets Curve hypothesis. The variables in the study consist of annual data from 1978 to 2022. First, the stationarity of the variables was tested using Augmented Dickey-Fuller (ADF) tests and Fourier ADF unit root tests with structural breaks, and all variables were found to be first-differenced stationary. In addition, causality between variables was examined using the Fourier Toda-Yamamoto causality test. For the first time in this context, the Fourier Bootstrap Autoregressive Distributed Lag (FARDL) Bound test was used to examine the cointegration relationship among the variables, and such a relationship was identified. The long-run estimation results of Fourier ARDL are as follows: I) The environmental Kuznets curve hypothesis is valid for South Korea. II) Nuclear energy consumption has a negative effect on CO_2 emissions (a 1% increase in nuclear energy consumption leads to a 0.11% decrease in CO_2 emissions in South Korea). III) Unidirectional causality was found from both CO_2 emissions and nuclear energy consumption to economic growth. Aligned with the research outcomes, the study concludes by outlining a series of policy recommendations for South Korea.

Keywords: Fourier Bootstrap ARDL, Nuclear Energy Consumption, EKC Hypothesis, Fourier ADF, Economic Growth

JEL Classification: C22, C51, P18, P28,Q43, Q50, Q53.

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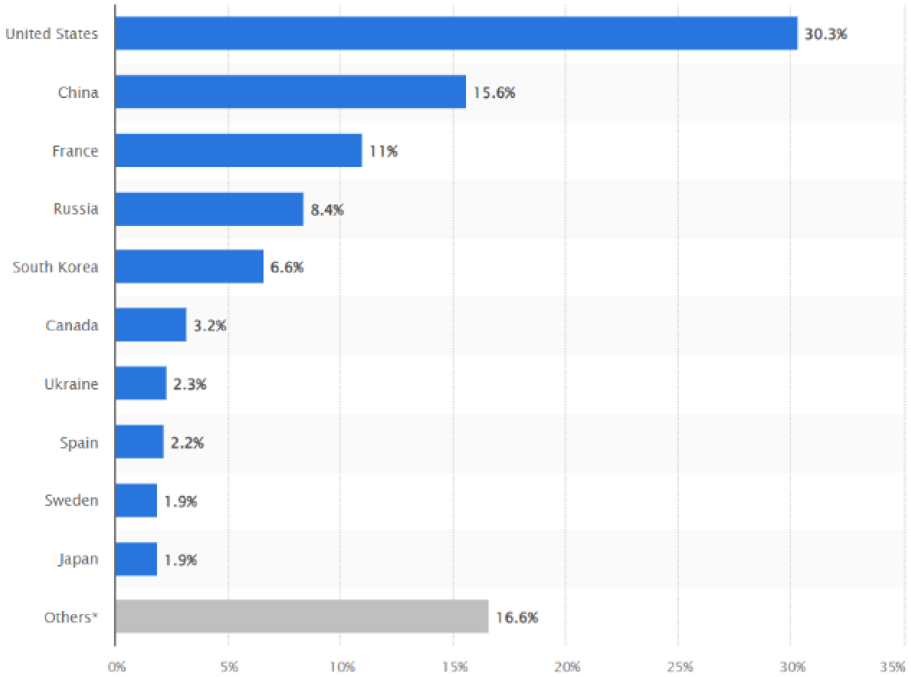
1. INTRODUCTION

The connection between nuclear energy consumption, CO_2 emissions, and economic growth has been a topic of discussion in recent economic literature. Generally, the findings indicate a strong relationship between nuclear energy usage and economic growth, CO_2 emissions and economic growth, as well as renewable energy consumption and economic growth. However, energy consumption raises significant concerns regarding environmental issues because while it can enhance economic growth, it is also a primary driver of environmental degradation. Currently, electricity generation heavily relies on fossil fuels, but with the expansion of nuclear energy and renewable energy-based production technologies, a substantial reduction in greenhouse gas emissions is expected in the future (Hoffert et al., 2002; Service, 2005; Rohatgi et al., 2002; Saidi and Mbarek, 2016).

As seen from the Figure 1, South Korea is in global top five nuclear energy consumption with 6.6 percent of its total energy consumption which corresponds to a combined net capacity of 25.8 GWe and 10,700 kWh per capita in 2022. This dependence is likely to continue, as evidenced by a recent government proposal aiming to raise nuclear power's share to 34.6% by 2036 through new reactor construction (World Nuclear Association, 2024). That is the why we focus on this important Asian high-tech industrialized economy.

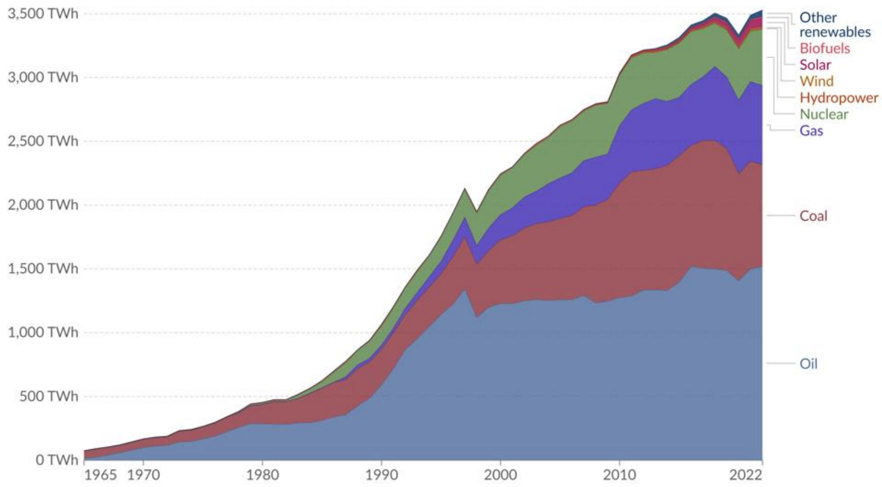
Figure 1: Distribution of nuclear power consumption worldwide in 2022



Source: Statista (2023)

As depicted on Figure 2 below, South Korea's energy consumption is well diversified among gas, nuclear, biofuels, hydro and other renewable sources. While fossil fuels dominate, the country is actively transitioning towards a more balanced mix. As of 2022, oil reigns supreme, accounting for about 1500 TWh in 2022, with applications primarily in transportation and non-energy uses like petrochemicals. Coal follows distantly, though its use has been declining due to environmental concerns. Natural gas consumption is increasing for power generation, but nuclear power remains a critical source, contributing around 28% of the electricity mix in 2022. Meanwhile, renewables like solar and wind are experiencing steady growth, driven by government initiatives to meet climate goals, but their overall contribution remains modest.

Figure 2: Energy consumption by source, South Korea



Source: Our World in Data (2023)

This paper studies the impact of nuclear energy consumption on CO_2 emissions in an industrialized Asian country, South Korea using Fourier Bootstrap ARDL Bound Test the first time in this context. Our finding suggest nuclear energy as an alternative clean energy source in South Korea for sustaining long-run economic growth and ensuring a sustainable environment. The rest of the paper is organized as following: Section 2 reviews the previous studies with a focus on gaps, Section 3 presents the data and model. We apply Fourier Bootstrap ARDL Bound test in Section 4. Empirical Results and Discussions are reported on Section 5 and followed by the Conclusion.

2. LITERATURE REVIEW

In this section of the study, the literature review is divided into two main categories. The first category comprises previous studies examining the relationship between economic growth and carbon emissions within the framework of the Environmental Kuznets Curve hypothesis. The second category includes earlier studies investigating the impact of nuclear energy consumption on carbon emissions.

2.1 Link Between Growth and CO_2 Emissions (EKC Hypothesis)

The relationship between economic growth and carbon emissions is investigated in the literature under the Environmental Kuznets Curve (EKC) hypothesis. Econometric models include economic growth and the square of economic growth for analysis. In this context, if economic growth has a positive coefficient while the square of economic growth has a negative coefficient, it is concluded that the EKC hypothesis holds true. For the first time, Grossman and Krueger (1991) investigated the Environmental Kuznets Curve (EKC) hypothesis for 42 countries using the panel Generalized Least Squares (GLS) method and provided evidence that the EKC hypothesis holds true for these countries. Eylasov et al. (2023) and Genç et al. (2022) investigated the validity of the Environmental Kuznets Curve (EKC) hypothesis in Turkey using the Autoregressive Distributed Lag (ARDL) method in their respective studies. Both studies concluded that the EKC hypothesis holds true in Turkey. In the study conducted by Mikayilov et al. (2018) in Azerbaijan, the relationship between economic growth and carbon emissions was investigated using the Johansen and Juselius method for the years 1992-2013. The study found that the Environmental Kuznets Curve (EKC) hypothesis was not valid in Azerbaijan. On the other hand, Pata (2018) examined the relationship between economic growth and carbon emissions in Turkey, taking into account structural breaks, using the Hatemi-J and Gregory-Hansen cointegration methods. The study concluded that the EKC hypothesis is valid in Turkey.

In their study on Kazakhstan, Hasanov et al. (2019) employed the Johansen and ARDLBT methods and found that the Environmental Kuznets Curve (EKC) hypothesis is not valid in Kazakhstan. Other studies are summarized briefly in Table 1.

Table 1. Relationship Between Economic Growth and CO_2 Emissions

Author(s)	Country(ies)	Data	Variables	Method	Results (EKC)
Eylasov et al. (2023)	Türkiye	1971-2019	$CO_2 = f(GDP, GDP^2, TFC)$	ARDL	Valid
Massagony and Budiono (2023)	Indonesia	1965-2020	$CO_2 = f(FE, RE, GDP, GDP^2)$	ARDL	Not Valid
Adebayo et al. (2023)	India	1970-2018	$CO_2 = f(NC, HG, EG, EG^2, GAS)$	ARDL	Valid
Velayutham (2023)	Sri Lanka	1971-2014	$CO_2 = f(CEN, URB, GDP, GDP^2, TRD)$	ARDL	Not Valid
Ma et al. (2021)	France and Germany	1995-2015	$CEPC = f(RE, TOUR, GPC, GPC^2, NRE, LAB)$	Pedroni and Westernlund	Valid
Ergun and Rivas (2020)	Uruguay	1971-2014	$EF = f(GDP, GDP^2, FDI, Energy)$	ARDL	Valid
Yilanci and Pata (2020)	China	1965-2016	$EF = f(GDP, EC)$	Fourier ARDL	Not Valid
Genç et al. (2022)	Turkiye	1980-2015	$CO_2 = f(EN, VOL, Y, Y^2)$	ARDL	Valid
Mikayilov et al. (2018)	Azerbaijan	1992-2013	$CO_2 = f(Y)$	Johansen and Juselius	Not Valid
Hasanov et al. (2019)	Kazakhstan	1992-2013	$CO_2 = f(GDP, GDP^2, GDP^3)$	Johansen and ARDLBT	Not Valid
Ali et al. (2021)	Pakistan	1975-2014	$CO_2 = f(ED, ED^2)$	ARDL	Valid
Pata (2018)	Turkiye	1974-2014	$CO_2 = f(URB, FD, Y, Y^2, REC, HEC, AEC)$	Gregory-Hansen and Hatemi-J	Valid
Sarkodie and Ozturk (2020)	Kenya	1971-2013	$CO2E = f(GDPPC, GDPPC^2, EGUSE, URBP)$	ARDL, SIMPLS, and U test	Valid
Pata et al. (2023)	Germany	1974-2018	$CO_2 = f(GDP, GDP^2, RRD, NRD)$	Fourier ADL	Valid
Islam et al. (2023)	Bangladesh	1976-2014	$CO_2 = f(GDP, CTI, URB, KAOPEN)$	ARDL	Not Valid
Sarkodie and Adams (2018)	South Africa	1971-2017	$CO_2E = f(RENE, NRENE, GDPPC, GDPPC^2, PIQ)$	ARDL	Valid
Zhang (2019)	Central Asia	1992-2013	$CO_2 = f(GDP, GDP^2, URB, RE)$	Pedroni and Westerlund	Not Valid
Van Chien (2020)	Vietnam	1990-2014	$EP = f(EC, EG, EG^2, TO)$	ARDL	Valid
Panayotou (1997)	30 countries	1982-1994	$SO_2 = f(GDP, POP, GDP^2)$	Panel GLS	Valid
Panayotou (1993)	55 countries	1985-1987	$DEF = f(INC, POP, INC^2)$	Panel Data	Valid
Akbota and Baek (2018)	Kazakhstan	1991-2014	$C = f(Y, Y^2, EC)$	ARDL	Valid
Grossman and Krueger (1991)	42 countries	1977-1988	$CO_2 = f(GDP, GDP^2)$	Panel GLS	Valid

2.2 Link Between Nuclear Energy Consumption and CO_2 Emissions

This section includes previous studies investigating the impact of nuclear energy consumption on CO_2 emissions. Upon reviewing the literature, it is observed that panel data and time series methods have been commonly employed in these studies, with the general finding that nuclear energy consumption tends to reduce carbon emissions. Although in limited numbers, some studies suggest a positive influence of nuclear energy consumption on carbon emissions. In the research by Pata and Kartal (2023), utilizing ARDL and Bayer-Hanck cointegration methods, the impact of nuclear energy consumption on CO_2 emissions in South Korea for the period 1977-2018 was investigated, and the conclusion was reached that nuclear energy consumption in South Korea leads to a reduction in CO2 emissions. Another study conducted for South Korea by Zimon et al. (2023) used ARDL boundary testing and found no significant impact of nuclear energy on CO2 emissions between 1972 and 2022. Jaforullah and King (2015) investigated the impact of nuclear energy consumption on carbon emissions in the United States using data spanning from 1966 to 2012. They employed the Johansen cointegration test, and the results indicated that nuclear energy consumption in the U.S. has a negative effect on carbon emissions. In another study conducted for the United States, Baek (2016) utilized ARDL boundary testing and found that nuclear energy positively influences carbon emissions in the U.S. Iwata et al. (2010) and Pata and Samour (2022) investigated the impact of nuclear energy consumption on carbon emissions in France using different time intervals and various time series methods. Both studies concluded that nuclear energy consumption has a negative effect on CO2 emissions in France. Ishida (2018) conducted a study on the impact of nuclear energy consumption on carbon emissions in Japan for the period 1970-2010 using the ARDL boundary testing approach. The findings indicated a positive effect of nuclear energy consumption on carbon emissions. In the study by Vo et al. (2020), which employed Kao and Westerlund panel cointegration methods, the influence of nuclear energy consumption on carbon emissions was investigated for Australia, Canada, Chile, New Zealand, Peru, Vietnam, Mexico, Japan, and Malaysia. The results suggested that in Australia, Canada, Chile, New Zealand, Peru, and Vietnam, nuclear energy contributed to a reduction in carbon emissions. However, in Mexico, Japan, and Malaysia, the use of nuclear energy was associated with an increase in carbon emissions. Nathaniel et al. (2021) utilized the Kao and Westerlund cointegration methods for the G7 countries between 1990 and 2017, finding that nuclear energy consumption had a negative impact on carbon emissions. In contrast, Jin and Kim (2018) concluded in their study that there was no significant effect of nuclear energy on carbon emissions in a selected sample of 30 countries. Mahmood et al. (2020) reported a positive influence of nuclear energy consumption on carbon emissions in Pakistan. Al-Mulali (2014) found, in a study involving the 30 largest nuclear energy-consuming countries, that nuclear energy consumption did not have a significant effect on carbon emissions. In other studies, Ozgur et al. (2022) observed negative effects of nuclear energy consumption on carbon emissions in India, Dong et al. (2018) in China, Lee et al. (2017) in 18 selected countries, and Saidi and Omri (2020) in 15 OECD countries. Table 2 summarizes studies investigating the impact of nuclear energy consumption on carbon emissions.

Table 2. Relationship Between Nuclear Energy (NE) and CO_2 Emissions

Author(s)	Country(ies)	Time Period	Variables	Method(s)	Results
Ozgur et al. (2022)	India	1970-2016	$CO_2 = f(GDP, GDP^2, NE)$	Fourier ARDL Cointegration	NE ↓ CO_2
Iwata et al. (2010)	France	1960-2003	$CO_2 = f(Y, Y^2, NUC, TR, EN, URB)$	ARDL Cointegration	NE ↓ CO_2
Saidi and Omri (2020)	15 OECD countries	1990-2018	$C = f(NE, RE, EG, FD, TO)$	Pedroni Cointegration	NE ↓ CO_2
Al-Mulali (2014)	30 major NE consuming countries	1990-2010	$CO_2 = f(NC, GDP, FC, UR)$	Pedroni co-integration	NE ∗ CO_2
Lee et al. (2017)	18 countries	1970-2015	$CO_2 = f(GDP, GDP^2, Nuclear, Renewable)$	Pedroni co-integration	NE ↓ CO_2
Naimoğlu (2023)	Pakistan	1971-2020	$CO_2 = f(NEC, GDP, GDP^2)$	Fourier Bootstrap ARDL	NE ↓ CO_2
Majeed et al. (2022)	Pakistan	1974-2019	$CO_2 = f(NE, GDP, GDP^2)$	ARDL	NE ↓ CO_2
Dong et al. (2018)	China	1993-2016	$CO_2 = f(GDP, GDP^2, NU, RE, FF)$	Bayer-Hanck cointegration	NE ↓ CO_2
Mahmood et al. (2020)	Pakistan	1973-2017	$CO_2 = f(GDP, GDP^2, NE)$	ARDL, Bayer-Hanck cointegration	NE ↑ CO_2

Jin and Kim (2018)	30 countries	1990–2014	*CE = f(RE, NE, Y, CP)*	Kao cointegration	NE ∗ CO_2
Jaforullah and King (2015)	US	1965-2012	*C = f(R, N, Y, P)*	Johansen cointegration	NE ↑ CO_2
Pata and Kartal (2023)	South Korea	1977-2018	$CO_2 = f(GDP, GDP^2, REC, NEC)$	ARDL and Bayer-Hanck	NE ↓ CO_2
Zimon et al. (2023)	South Korea	1972-2021	$CO_2 = f(GDP, POP, REN, NUC, FOS)$	ARDL, FMOLS and DOLS	NE ∗ CO_2
Nathaniel et al. (2021)	G7	1990-2017	$CO_2 = f(RE, NE, GR, GR^2)$	Kao and Westerlund	NE ↓ CO_2
Pata and Samour (2022)	France	1977-2017	$CO_2 = f(REC, NEC, GDP)$	Fourier ARDL	NE ↓ CO_2
Baek (2016)	US	1960-2010	$CO_2 = f(Y, EN, NUC, REN)$	ARDL Cointegration	NE ↓ CO_2
Ishida (2018)	Japon	1970-2010	*CDE = f(Y, NUC, EPR)*	ARDL Cointegration	NE ↑ CO_2

Notes: ↑; Positive impact, ↓; negative impact, ∗; insignificant impact.

3. MODEL AND DATA

The econometric model presented in Equation 1, as included in the studies by (Mahmood et al., 2020; Naimoğlu, 2023; Ozgur et al., 2022; Majeed et al., 2022), has been established to investigate the impact of nuclear energy consumption on CO_2 emissions in South Korea within the framework of the Environmental Kuznets Curve hypothesis.

$$LCO_{2t} = \beta_1 + \beta_2 LGDP_t + \beta_3 LGDP_t^2 + \beta_4 LNE_t + u_t \tag{1}$$

Where β_1 is the intercept and u_t is the error term. A positive value for the coefficient β_2 and a negative value for β_3 would indicate the validity of the Environmental Kuznets Curve hypothesis in South Korea (Van Chien, 2020; Akbota and Baek, 2018; Ma et al., 2021). On the other hand, we theoretically expect nuclear energy consumption to have a negative impact on CO_2 emissions. Therefore, the coefficient β_4 should be negative (Dong et al., 2018; Pata and Samour, 2022; Nathaniel et al., 2021). Table 3 shows the definitions of the variables used in the study. All the variables have been log transformed.

Table 3. Variables details.

Variables	Symbol	Unit	Reference
Carbon Dioxide Emissions	CO_2	Million tonnes of carbon dioxide	Our World in Data (2023)
GDP per capita	GDP	Constant 2015 US$	World Bank (2023)
Nuclear Energy Consumption	NE	Exajoules (input-equivalent)	Our World in Data (2023)

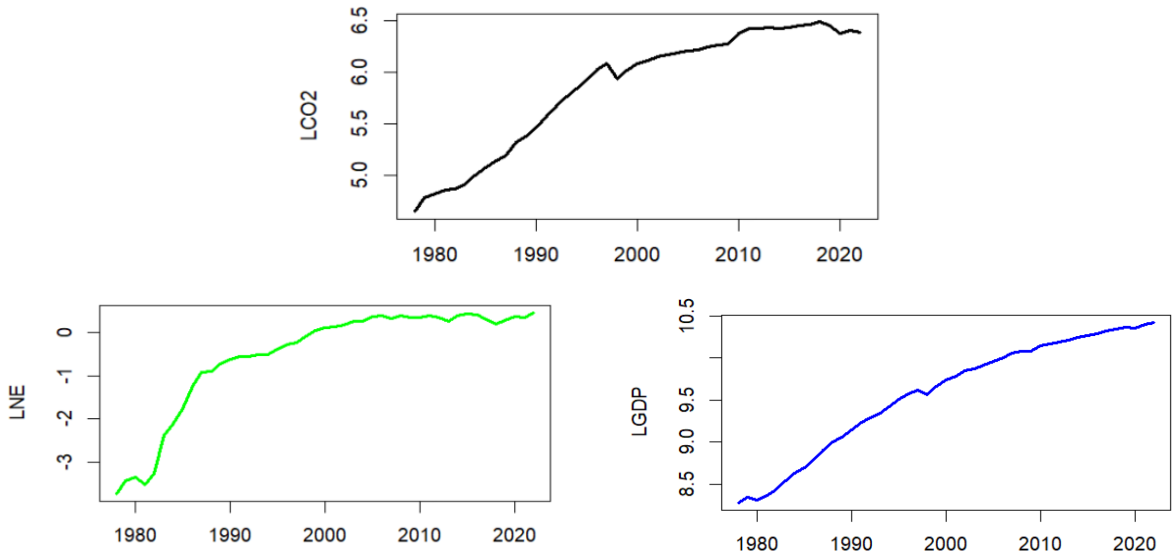
The descriptive statistics for all variables are presented in Table 4. The variables used in the study exhibit a normal distribution, as evidenced by the Jarque-Bera test statistics' probability values being greater than 0.05, leading to the non-rejection of the null hypothesis. Additionally, in South Korea, the minimum and maximum per capita income are observed to be \$3919 and \$33719, respectively. On the other hand, the skewness values for carbon emissions and nuclear energy consumption variables are negative, indicating a left-skewed normal distribution graph, while the skewness coefficient for the economic growth variable is positive, suggesting a right-skewed normal distribution graph. As all kurtosis values for the variables are less than 3, the normal distribution graph for each variable will have a horizontal shape. The study encompasses a data range from 1978 to 2022, comprising 45 observation values.

Table 4. Descriptive statistics.

	CO_2	GDP	NE
Mean	404.2178	17470.26	0.910222
Median	438.2000	16995.56	1.110000
Maximum	659.1000	33719.39	1.590000
Minimum	104.0000	3913.833	0.020000
Std. Dev.	186.6468	9634.823	0.540801
Skewness	-0.271037	0.100711	-0.403226
Kurtosis	1.621928	1.650688	1.638913
Jarque-Bera	4.111737	3.489775	4.692975
Probability	0.127982	0.174665	0.095705
Observations	45	45	45

Figure 3 displays the time series graphs of the variables used in the study. Structural breaks in economic growth and carbon emission variables are observed in South Korea due to the 1997 Asian financial crisis. Additionally, all variables exhibit an increasing trend. Examining the graph of South Korea's nuclear energy consumption, it is evident that nuclear energy consumption has shown a rapid increase since 1981. The presence of a positive trend in the variables is considered in unit root tests, where the results of both constant and trend models are taken into account.

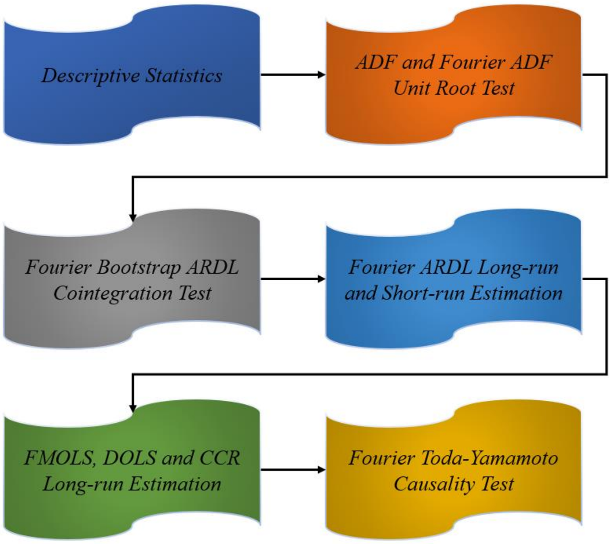
Figure 3. Time paths of the variables.



4. METHODOLOGY

In this section, a brief description of the econometric methods used in the study will be provided. First, the descriptive statistics of the variables are presented, followed by testing for stationarity using the ADF and Fourier ADF unit root tests. To investigate the cointegration relationship between the variables, the Fourier Bootstrap ARDL Bound test is used for the first time in the context of South Korea. The long and short-run estimation results are initially reported using the FB-ARDL method, followed by only the long-run estimation results using the FMOLS, DOLS, and CCR methods. Finally, the causal relationship between the variables is examined using the Fourier Toda Yamamoto causality test. Figure 4 illustrates the econometric methodology step by step.

Figure 4. Methodology way.



4.1 Unit Root Tests

In the study, the stationarity of the variables was tested using the Augmented Dickey-Fuller (ADF) unit root tests by Dickey and Fuller (1981) and the Flexible Fourier Augmented Dickey-Fuller unit root tests by Enders and Lee (2012). The unit root test was first introduced to the literature by Dickey and Fuller (1979). Due to the issue of autocorrelation in the DF test, Dickey and Fuller (1981) introduced the Augmented Dickey-Fuller unit root test to address this issue. The regression equations for the Augmented Dickey-Fuller unit root test are as follows.

$$\Delta Y_t = \alpha Y_{t-1} + \sum_{k=1}^{k} \theta_k Y_{t-k} + u_t \tag{2}$$

$$\Delta Y_t = \beta_1 + \alpha Y_{t-1} + \sum_{k=1}^{k} \theta_k Y_{t-k} + u_t \tag{3}$$

$$\Delta Y_t = \beta_1 + \beta_2 t + \alpha Y_{t-1} + \sum_{k=1}^{k} \theta_k Y_{t-k} + u_t \tag{4}$$

When the nuclear energy consumption (NE) variable is adapted to the equations above, they take the following form.

$$\Delta NE_t = \alpha NE_{t-1} + \sum_{k=1}^{k} \theta_k NE_{t-k} + u_t \tag{5}$$

$$\Delta NE_t = \beta_1 + \alpha NE_{t-1} + \sum_{k=1}^{k} \theta_k NE_{t-k} + u_t \tag{6}$$

$$\Delta NE_t = \beta_1 + \beta_2 t + \alpha NE_{t-1} + \sum_{k=1}^{k} \theta_k NE_{t-k} + u_t \tag{7}$$

In the equations above, the term β_1 represents the constant term, $\beta_2 t$ denotes the time trend, and u_t represents the error term. The lag length k is automatically determined using the SC or AIC information criteria. If k is found to be 1, the lag of the first difference of the variable will be added to the model to address the autocorrelation issue. Here, the presence of a unit root in nuclear energy consumption is tested using the α coefficient. If the tau statistic value at one lag of the variable is found to be greater than the MacKinnon (1996) critical values, the null hypothesis of 'a unit root exists, the variable is non-stationary' will be rejected. In other words, the nuclear energy consumption variable will be stationary at level. The Augmented Dickey-Fuller (ADF) unit root test does not provide reliable results under structural breaks. Therefore, in their study, Enders and Lee (2012) aimed to improve the performance of the classic ADF unit root test under structural breaks by adding Fourier terms, specifically sine and cosine terms, to the ADF equation. The regression models for the Flexible Fourier ADF unit root test proposed in the Enders and Lee (2012) study are shown below.

$$\Delta NE_t = \alpha NE_{t-1} + \phi_1 \sin\left(\frac{2\pi kt}{T}\right) + \phi_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{k} \theta_k NE_{t-k} + u_t \qquad (8)$$

$$\Delta NE_t = \beta_1 + \alpha NE_{t-1} + \phi_1 \sin\left(\frac{2\pi kt}{T}\right) + \phi_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{k} \theta_k NE_{t-k} + u_t \qquad (9)$$

$$\Delta NE_t = \beta_1 + \beta_2 t + \alpha NE_{t-1} + \phi_1 \sin\left(\frac{2\pi kt}{T}\right) + \phi_2 \cos\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{k} \theta_k NE_{t-k} + u_t \qquad (10)$$

In the equations above, k represents the frequency, t denotes the trend, and T is the number of observations. As is well known, π is 3.1415. The frequency k is tested from 1 to 5. The crucial aspect here is finding the sine and cosine terms to be statistically significant. If ϕ_1 and ϕ_2 are not found to be significant, it implies that there is no structural break in the variable and the results of the classical ADF model will be valid. On the other hand, if the sine and cosine terms are statistically significant and the α test statistic is found to be greater than the critical values provided by Enders and Lee (2012), the null hypothesis will be rejected, and the series will be deemed stationary at level according to the FADF test.

4.2 Cointegration Tests

In the study, the presence of a cointegration relationship between variables was examined for South Korea for the first time within the scope of the topic using the Fourier Bootstrap ARDL bound testing approach introduced to the literature by Yilanci et al. (2020). Although there are numerous cointegration tests available in the literature, these tests generally allow for the investigation of a cointegration relationship between variables only when all variables are stationary at the same level. The ARDL bound testing approach, first introduced to the literature by Pesaran et al. (2001), enables the investigation of a cointegration relationship when the dependent variable is stationary in its difference form, while the independent variables are stationary at different levels. However, none of the variables should be stationary in their second difference form. The ARDL bound test equation adapted to the variables in the study is as follows.

$$\Delta LCO2_t = \alpha + \sum_{i=1}^{p} \beta_{1i} \Delta LCO2_{t-i} + \sum_{i=0}^{q} \beta_{2i} \Delta LGDP_{t-i} + \sum_{i=0}^{m} \beta_{3i} \Delta LGDP^2{}_{t-i} + \sum_{i=0}^{n} \beta_{4i} \Delta LNE_{t-i} + \gamma_1 LCO2_{t-1} + \gamma_2 LGDP_{t-1} + \gamma_3 LGDP^2{}_{t-1} + \gamma_4 LNE_{t-1} + v_t \qquad (11)$$

Where Δ denotes the difference series of the variables and v_t denotes the error term. The lag lengths p, q, m, and n are automatically determined using the AIC and SC information criteria. In the ARDL bound testing approach by Pesaran et al. (2001), there are two test statistics: $F_{overall}$ and $t_{depented}$. If the $F_{overall}$ statistic is found to be greater than the critical values specified by Narayan (2005), or the $t_{depented}$ statistic exceeds the critical values reported in the Pesaran et al. (2001) study, the null hypothesis will be rejected. This indicates the presence of a cointegration relationship among the variables. As previously mentioned, the ARDL bound test allows for the investigation of a cointegration relationship when the dependent variable is I(1). To address this issue and to obtain good results even when more independent variables are used, the Augmented ARDL and Bootstrap ARDL approaches were introduced to the literature by Sam et al. (2019) and McNown et al. (2018), respectively. In these studies, along with the $F_{overall}$ and $t_{depented}$ tests, the $F_{indepented}$ test was also proposed. If the $F_{indepented}$ test statistic is found to be greater than the critical values specified in Sam et al. (2019), the null hypothesis will be rejected. Therefore, all three tests need to exceed the critical values. In the study by Yilanci et al. (2020), the Fourier Bootstrap ARDL approach was introduced to the literature by adding sine and cosine terms to the equation presented in Equation 11. The Fourier terms added to Equation 11 transform it into the equation given in Equation 12.

$$\Delta LCO2_t = \alpha + \Phi_1 sin\left(\frac{2\pi kt}{T}\right) + \Phi_2 cos\left(\frac{2\pi kt}{T}\right) + \sum_{i=1}^{p} \beta_{1i} \Delta LCO2_{t-i} + \sum_{i=0}^{q} \beta_{2i} \Delta LGDP_{t-i} + \sum_{i=0}^{m} \beta_{3i} \Delta LGDP^2{}_{t-i} + \sum_{i=0}^{n} \beta_{4i} \Delta LNE_{t-i} + \gamma_1 LCO2_{t-1} + \gamma_2 LGDP_{t-1} + \gamma_3 LGDP^2{}_{t-1} + \gamma_4 LNE_{t-1} + v_t \qquad (12)$$

Where π is 3.1415, k represents the frequency and is tested from 0.1 to 5. t denotes the trend and T represents the number of observations. The hypotheses for the calculated $F_{overall}$, $t_{depented}$, and $F_{indepented}$ test statistic values are as follows.

$F_{overall} = H_0 : \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 0$

$t_{depented} = H_0 : \gamma_1 = 0$

$F_{indepented} = H_0 : \gamma_2 = \gamma_3 = \gamma_4 = 0$

If all test statistic values are found to be greater than the calculated bootstrap critical values, the null hypothesis will be rejected, indicating the presence of a cointegration relationship among the series (Aghayeva and Zortuk, 2024).

4.3 Causality Test

In the study, the Fourier Toda-Yamamoto causality test, introduced to the literature by Nazlioglu et al. (2016), is used to examine the causality relationship among the variables. Toda-Yamamoto causality test, created by Toda-Yamamoto (1995), eliminates the issues with the conventional Granger causality test by rejecting potential non-stationarity or cointegration between the series, as demonstrated by Zapata and Rambaldi (1997) and Wolde-Rufael (2004, 2005). By applying a VAR model to the series' level values, the Toda and Yamamoto (1995) technique minimizes the possibility that the series' integration order may be incorrectly specified (Mavrotas and Kelly, 2001). Since the TY causality test does not yield reliable results under structural breaks, the Fourier Toda-Yamamoto causality test is recommended by Nazlioglu et al. (2016). Using the following system of equations, we demonstrate the Granger causality test inside the overall structure of the $LCO2_t$ $LGDP_t$ $LGDP_t^2$ LNE_t model to apply the Fourier Toda-Yamamoto (FTY) version:

$$\begin{bmatrix} LCO2_t \\ LGDP_t \\ LGDP_t^2 \\ LNE_t \end{bmatrix} = \begin{bmatrix} \beta_{10} \\ \beta_{20} \\ \beta_{30} \\ \beta_{40} \end{bmatrix} + \sum_{i=1}^{k} \begin{bmatrix} \beta_{11,i} & \beta_{12,i} & \beta_{13,i} & \beta_{14,i} \\ \beta_{21,i} & \beta_{22,i} & \beta_{23,i} & \beta_{24,i} \\ \beta_{31,i} & \beta_{32,i} & \beta_{33,i} & \beta_{34,i} \\ \beta_{41,i} & \beta_{42,i} & \beta_{43,i} & \beta_{44,i} \end{bmatrix} \begin{bmatrix} LCO2_{t-i} \\ LGDP_{t-i} \\ LGDP_{t-\imath}^2 \\ LNE_{t-\imath} \end{bmatrix} +$$

$$+\sum_{j=1}^{d_{max}} \begin{bmatrix} \beta_{11,k+j} & \beta_{12,k+j} & \beta_{13,k+j} & \beta_{14,k+j} \\ \beta_{21,k+j} & \beta_{22,k+j} & \beta_{23,k+j} & \beta_{24,k+j} \\ \beta_{31,k+j} & \beta_{32,k+j} & \beta_{33,k+j} & \beta_{34,k+j} \\ \beta_{41,k+j} & \beta_{42,k+j} & \beta_{43,k+j} & \beta_{44,k+j} \end{bmatrix} \begin{bmatrix} LCO2_{t-(k+j)} \\ LGDP_{t-(k+j)} \\ LGDP_{t-(k+j)}^2 \\ LNE_{t-(k+j)} \end{bmatrix}$$

$$+\sum_{k=1}^{n} \begin{bmatrix} \gamma_{11} \\ \gamma_{21} \\ \gamma_{31} \\ \gamma_{41} \end{bmatrix} \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \begin{bmatrix} \gamma_{12} \\ \gamma_{22} \\ \gamma_{32} \\ \gamma_{42} \end{bmatrix} \cos\left(\frac{2\pi kt}{T}\right) + \begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \varepsilon_{3,t} \\ \varepsilon_{4,t} \end{bmatrix} \tag{13}$$

In this case, k is the optimum lag length, which ranges from $i = 1,2,3 \dots t-1$. β_{i0} are the constant term, $\beta_{ij,i}$ are are the coefficients of the variables taking into consideration the lag length, $\overline{\imath,\jmath} = 1, \dots, 4$, and d_{max} = the maximum order of integration. Considering the maximum order of integration and the lag time, the coefficients of the variables are $\beta_{ij,k+j}$ and $j = 1,2,..,t-k-1$. The stochastic or error terms are denoted by $\varepsilon_{i,t}$ $\bar{\imath} = 1, \dots, 4$. To examine the causal relationship between $LCO2_t$ and $LGDP_t$ for instance, the following hypothesis should be investigated.

$H_0^{GDPPC_t \to CO_{2,t}}$: $\beta_{21,1} = \beta_{21,2} = \cdots = \beta_{21,k} = 0$

$H_1^{GDPPC_t \to CO_{2,t}}$: $\beta_{21,1} \neq \beta_{21,2} \neq \cdots \neq \beta_{21,k} \neq 0$

The test result indicates that there is no causal association from LGDP to LCO2, if the null hypothesis cannot be rejected. If not, it is determined that there is a causal connection from LGDP to LCO2. Analogously, potential causal relationships between other variables can also be examined.

5. EMPIRICAL RESULTS AND DISCUSSION

In this section, the stationarity of the variables was first tested. The stationarity results of the variables tested with the Fourier ADF and ADF unit root tests are presented in Table 5. When looking at the Fourier ADF test results, it is observed that the F test, which tests the significance of the Fourier terms (sine and cosine), is not statistically significant. Therefore, according to the Fourier ADF test, since there is no significant break in the variables, the results of the classical ADF unit root test will be valid. According to the ADF unit root test results, all variables are found to be stationary at their first difference. Hence, all variables are I(1).

Table 5. Unit root test results.

Model	Fourier ADF		ADF	
Constant and Trend			Level	First Differences
Variables	F test	Test Statistics	Test Statistics	Test Statistics
LCO$_2$	2.580	-0.146 {2} [0]	0.029 (0.99) [0]	-6.291^{***} (0.00) [0]
LGDP	5.081	-2.249 {1} [0]	-0.006 (0.99) [0]	-5.952^{***} (0.00) [1]
LNE	1.554	-1.903 {4} [1]	-2.012 (0.57) [0]	-4.730^{***} (0.00) [0]

Note: *** and * shows significance at the 1% and 10% level, respectively. Numbers in parenthesis, bracelets, and brace indicate p-values, optimal lag-length chosen as using Akaike information criteria, and optimal frequency chosen using the sum of squared residuals. The 10% critical value for the F test is 7.78.

Since the variables were found to be stationary at their first difference, the cointegration relationship between the variables can be tested using the Fourier Bootstrap ARDL bounds test. The results of the Fourier Bootstrap ARDL bounds test are presented in Table 6. According to the FB-ARDL test results, all F_{all}, $t_{dependent}$, and $F_{independent}$ test statistics are greater in absolute value than the bootstrap critical values, so the null hypothesis of 'no cointegration' is rejected. Therefore, according to all test statistic results, a cointegration relationship has been found among the variables.

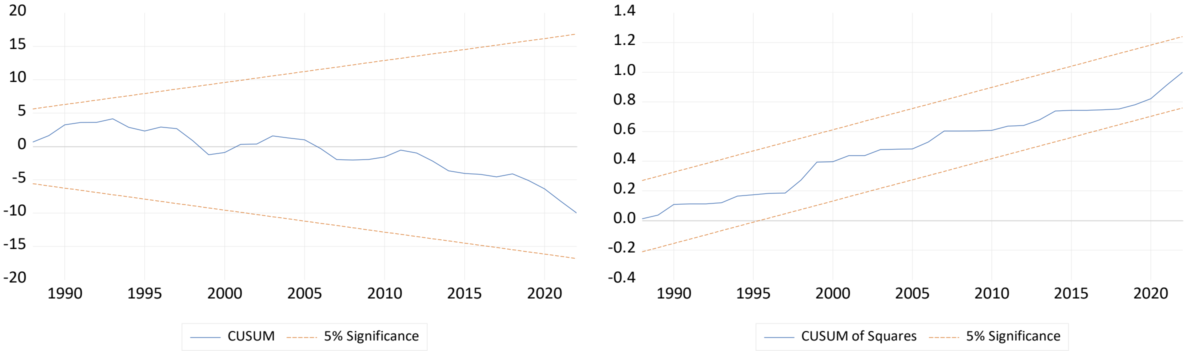
Table 6: Fourier Bootstrap ARDL cointegration test results.

Selected Model		Optimal Frequency		AIC
Fourier ARDL (1,1,1,0)		2.60		-4.668
		Bootstrap Critical Values		
Test Statistics		0.90	0.95	0.99
F_{all}	5.007^{***}	2.607	3.256	4.820
$t_{dependent}$	-2.795^{***}	-1.335	-1.801	-2.791
$F_{independent}$	5.312^{**}	2.722	3.359	5.876
Diagnostic test results				
Tests	Statistics	Prob		
Jarque-Bera	1.366	0.504		
Breusch-Godfrey LM	1.787	0.183		
Breusch-Pagan-Godfrey	0.681	0.704		
CUSUM	Stable			
CUSUMsq	Stable			

Note: We performed 2000 simulations to obtain the critical values. *** and ** shows significance at the 1% and 5% level, respectively.

For the cointegration relationship found among the variables using the FB-ARDL bounds test in Table 6 to be valid, the diagnostic test results must also be valid. Table 6 also includes the diagnostic test results of the FB-ARDL model. Since the p-values of the Jarque-Bera normality test, Breusch-Godfrey LM autocorrelation test, and Breusch-Pagan-Godfrey heteroscedasticity test are greater than 0.05, there are no issues of normality, autocorrelation, and heteroscedasticity in the residuals of the FB-ARDL model, respectively. Additionally, Figure 5 shows the CUSUM and CUSUMsq graphs. Upon examining the graphs, since the estimated parameters lie within the confidence interval, the model is considered stable. Therefore, the cointegration test found using the FB-ARDL bounds test is valid.

Figure 5. CUSUM and CUSUMsq



Since a cointegration relationship is found between the variables, long-run estimation results can be reported. Table 7 presents the Fourier ARDL long and short-run estimation results, as well as the short-term error correction model. According to the long-run estimation results in Table 7, the coefficients are statistically significant, indicating that in the long run, the economic growth variable positively affects carbon emissions, while the square of the economic growth variable negatively affects carbon emissions. Therefore, in the long run, the Environmental Kuznets Curve hypothesis is valid in South Korea. This finding is consistent with the studies of Ergun and Rivas (2020), Ma et al. (2021), Adebayo et al. (2023), and Genç et al. (2022), but inconsistent with the studies of Zhang (2019) and Massagony and Budiono (2023). Additionally, in the long run, nuclear energy consumption negatively affects carbon emissions. A 1% increase in nuclear energy consumption in South Korea will lead to an average decrease of 0.11% in carbon emissions. This finding aligns with the studies of Pata and Kartal (2023), Dong et al. (2018), and Majeed et al. (2022), but does not align with the studies of Zimon et al. (2023) and Mahmood et al. (2020).

Looking at the short-run estimation results in Table 7, it can be seen that in the short run, the economic growth variable negatively affects carbon emissions, while the square of the economic growth variable positively affects carbon emissions. Therefore, in the short run, the Environmental Kuznets Curve hypothesis is not valid in South Korea. There is a U-shaped relationship between economic growth and carbon emissions variables. Finally, the error correction coefficient is statistically significant and has a negative value. This means that deviations from the equilibrium that occur in the short run will adjust to the long-run equilibrium at a rate of 47%.

Table 7: Fourier ARDL long-run and short-run estimation results.

Panel A: Long-run estimation results.				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
$LGDP$	5.596416	1.201968	4.656043	0.000
$LGDP^2$	-0.246685	0.059427	-4.151089	0.000
LNE	-0.115140	0.051258	-2.246289	0.031
Panel B: Short-run estimation results.				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
$\Delta LGDP$	-3.996	1.102	-3.624	0.000
$\Delta LGDP^2$	0.269	0.060	4.488	0.000
SIN	0.004	0.005	0.871	0.389
COS	0.028	0.045	6.242	0.000
ECT	-0.478	0.071	-6.654	0.000

The study also reports long-run estimation results using FMOLS, DOLS, and CCR methods. The long-run estimation results from FMOLS, DOLS, and CCR are presented in Table 8. As with the long-run estimation results from FB-ARDL, the Environmental Kuznets Curve hypothesis is valid in South Korea according to the long-run estimation results from FMOLS, DOLS, and CCR. On the other hand, nuclear energy consumption negatively affects carbon emissions in the long run across all three methods.

Table 8: Robustness check for long-run estimation.

FMOLS	Coefficient	Std. Error	t-Statistic	Prob.
LGDP	10.307	1.220	8.444	0.000
$LGDP^2$	-0.475	0.060	-7.832	0.000
LNE	-0.316	0.051	-6.157	0.000
DOLS	Coefficient	Std. Error	t-Statistic	Prob.
LGDP	9.525	2.181	4.366	0.000
$LGDP^2$	-0.438	0.106	-4.110	0.000
LNE	-0.271	0.081	-3.328	0.002
CCR	Coefficient	Std. Error	t-Statistic	Prob.
LGDP	10.341	1.254	8.245	0.000
$LGDP^2$	-0.477	0.062	-7.653	0.000
LNE	-0.313	0.051	-6.021	0.000

Lastly, to investigate the causal relationship between the variables, the study employed the Fourier Toda Yamamoto causality test, which has been frequently used in recent literature. The results of the Fourier Toda-Yamamoto causality test are presented in Table 9, indicating a unidirectional causality from both carbon emissions and nuclear energy consumption to economic growth.

Table 9: Fourier Toda-Yamamoto Causality Test Results.

Direction	Chi sq	Frequency	Prob
LCO2→LGDP	12.360***	1	0.000
LGDP→LCO2	0.0227	1	0.880
LCO2→LNE	0.4767	1	0.489
LNE→LCO2	1.2010	1	0.273
LGDP→LNE	2.2609	1	0.132
LNE→LGDP	3.8675**	1	0.049

Note: *** and ** shows significance at the 1% and 5% level, respectively.

6. CONCLUSION

Energy security and climate change have become significant challenges faced by many countries. Such concerns have brought the importance of nuclear and renewable energy to the forefront of wider energy discussions. Nuclear and renewable energy play a crucial role not only in ensuring energy security but also in reducing emissions. In this study, the impact of nuclear energy consumption on carbon emissions in South Korea was investigated within the framework of the Environmental Kuznets Curve Hypothesis. For the first time in the literature, the Fourier Bootstrap ARDL approach was employed to examine the cointegration relationship among variables, revealing a long-run relationship. According to the long-term forecast results of FB-ARDL, the Environmental Kuznets Curve holds true in South Korea, with nuclear energy consumption exerting a negative influence on carbon emissions over the long term. Specifically, a 1% increase in nuclear energy consumption in South Korea will lead to an average decrease of 0.11% in carbon emissions. Additionally, the study utilized the Fourier Toda-Yamamoto causality test to explore the causal relationship between variables, uncovering a unidirectional causality from carbon emissions and nuclear energy consumption towards economic growth. The findings in this study provide evidence supporting the role of nuclear energy as an alternative clean energy source in South Korea for sustaining long-run economic growth and ensuring a sustainable environment. In this study, it is suggested as a first step for policymakers to expand the capacity of nuclear power plants to achieve sustainable and clean growth. The short-term forecast results also support the critical role of nuclear energy as a clean energy source and an effective alternative to fossil fuels in reducing environmental degradation. The use of nuclear energy in electricity generation will also contribute to energy security for South Korea. Policymakers are recommended to be aware of the potential hazards and security issues associated with nuclear energy production. Therefore, it is essential for policymakers to implement security measures in nuclear power plants to prevent disasters.

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