The Impact of Fossil Fuels, Renewable Energy, and Nuclear Energy on South Korea’s Environment Based on the STIRPAT Model: ARDL, FMOLS, and CCR Approaches

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Abstract: This study intends to shed light on the environmental impacts of energy decisions in South Korea by analyzing the correlation between energy consumption patterns and environmental indicators such as carbon dioxide emissions. In 2021, global CO₂ emissions increased by 6%—to the highest ever level of 36.3 billion tons—according to the International Energy Agency (IEA). This increase in CO₂ emissions is a big problem for all countries around the world. The aim of this article is to analyze the impact of fossil fuels, renewable energy, and nuclear energy on South Korea’s environment based on the STIRPAT (stochastic impact by regression on population, affluence, and technology) model. Exploring the intricate nexus between economic and energy indicators and environmental outcomes, this study employs the STIRPAT model to analyze the influence of GDP, population dynamics, fossil fuels, renewable energy, and nuclear energy on South Korea’s environment. The yearly data from 1972 to 2021 are analyzed in this paper using an autoregressive distributed lag (ARDL) model. The reliability of this study is also examined by employing FMOLS (fully modified ordinary least squares) and CCR (canonical cointegrating regression) estimators. This study confirms the findings of previous research by showing that the rising South Korea GDP and population can lead to higher CO₂ emissions and that a strategy switching to renewable energy can cut down on CO₂ emissions in Korea, as it exhibits a coefficient of −0.085 *. The robustness results of FMOLS and CCR’s findings support baseline ARDL findings.

Keywords: ARDL; CO₂ emission; renewable energy; fossil fuels; STIRPAT model; Korea

1. Introduction

Human activities like the burning of oil, coal, and gas, as well as deforestation, are the primary generators of carbon dioxide and other greenhouse gases. Thermal power facilities using fossil fuels are the primary human-made sources of CO₂ emissions. The deterioration of the natural environment is the single biggest threat to the long-term viability of the human race [1,2]. Heightened levels of carbon dioxide in the atmosphere can be attributed mostly to human activity, including the combustion of fossil fuels such as oil, coal, and gas, as well as the widespread practice of deforestation. The combustion of fossil fuel accounts for approximately 87 percent of carbon dioxide emissions resulting from human activities [3].
Current scholarly investigations have necessitated a concentrated effort toward addressing the global issue of environmental degradation. One of the primary factors contributing to the degradation of ecosystems is dependence on nonrenewable energy resources. Consequently, in order to foster low-carbon economies, policymakers are currently placing more emphasis on the advancement of renewable energy generation and utilization throughout many sectors of the economy [4]. Furthermore, the consequences of both renewable and nonrenewable energy sources have seen significant transformations in recent years, mostly due to the influence of the Intergovernmental Panel on Climate Change (IPCC) and the United Nations (UN) agreements. Renewable and nonrenewable energy sources have a significant impact on the environment, making environmental preservation and protection a crucial aspect of a sustainable future. Consequently, these two forms of energy are recognized as key contributors to the achievement of sustainable development goals. In addition to its ecological implications, clean energy exerts influence on several dimensions of a sustainable future. The research conducted by Zhao et al. [5] demonstrates that the utilization of renewable energy sources effectively mitigates the issue of energy poverty.

Nuclear power, being a relatively clean energy option, can help with a wide variety of environmental concerns, including limiting the effects of climate change, enhancing air quality, and diminishing levels of fine particles [6]. Different types of fission nuclear power plants are available. Light water reactors (LWRs) have been utilized for the production of electrical energy for a period exceeding five decades, serving as a reliable source of power for the electrical grids of over 20 nations. The PWR and BWR kinds of light water reactors have been shown to be highly reliable and efficient over many years. Keeping nuclear power available as a potential source of energy is advocated by many as being beneficial to society as a whole. Public, utility, government, and financial support for nuclear power are all necessary for its widespread adoption. This necessitates having faith in the stability and cost-effectiveness of reactors. Several cutting-edge reactor concepts are being explored with the goal of doing this [7]. Boiling water reactors were introduced into the commercial market in the latter part of 1950. The development of BWR technology took place at Argonne National Laboratory (ANL) and the Nuclear Energy Division (NED) of General Electric Company (GE) [8]. The boiling water reactor (BWR) is considered to be a highly simplified structure for a nuclear reactor, as it eliminates the need for supplementary heat exchangers or steam generators. Nevertheless, the internal mechanisms within a boiling water reactor (BWR) exhibit a high degree of intricacy. The steam pressure and temperature in a conventional coal-fired power plant are relatively lower as compared to those in a contemporary facility. Additionally, the steam turbines employed in such power plants tend to be of considerable size. Boiling water reactors (BWRs) possess power generation capacities reaching up to 1400 MW while exhibiting an approximate efficiency of 33% [9]. The pressurized water reactor (PWR) is a nuclear reactor variant employed for the purpose of energy generation and the propulsion of nuclear submarines and naval vessels. The coolant and neutron moderator employed in their system is light water, which refers to ordinary water rather than heavy water. The mentioned reactor is classified as one of three variants of light water reactors, namely the boiling water reactor and the supercritical water-cooled reactor [10]. The molten salt fast reactor (MSFR) concept, which employs a circulating fuel that simultaneously serves as a coolant and operates within a fast neutron spectrum, is regarded as a viable and sustainable alternative to solid-fueled fast reactors in the long run. This particular technology meets the standards established for Generation-IV reactors and has been the subject of research for approximately ten years, primarily through computational modeling and the investigation of fundamental physical and chemical characteristics within the European Union and the Russian Federation [11].

The whole world knows about it and is trying to take actions that will at least reduce CO₂ emissions into the atmosphere. Unfortunately, these activities often collide with an economic barrier. The rulers must decide on what is more important: economic development or the health of citizens. In addition, in Poland, politics has a large impact on energy strategy [12,13], especially when energy from fossil fuels is the issue to discuss.
In Poland, society has been subsidizing the maintenance of unprofitable mines for years. The rulers are afraid to introduce changes in this respect, as rational changes leading to a reduction in CO$_2$ emissions and an improvement in the mines’ profitability may lead to the liquidation of jobs in mines, which in turn will negatively affect the ratings of the ruling party. Therefore, the rulers face a choice whether to take care of their jobs and their families working in state-owned companies or try to improve the energy policy of Poland, which would certainly have a positive impact on air quality and the health of citizens [12–15].

As the studies of many authors show, it is difficult to choose the right energy strategy to both maintain economic development at a high level and at the same time strongly reduce pollution and environmental devastation. This is a big problem which, in the case of Poland, no government has dealt with so far. An additional problem in the case of energy policy in the world appeared at the outbreak of the war in Ukraine. In the first months of the war, the demand for coal increased, which no one expected. Analyzing the macroeconomic situation, it is clear that today the creation of an appropriate, optimal energy policy in the country is a huge challenge for the rulers.

Unfortunately, the Korean government is more concerned with boosting the economy than protecting the environment. By 2030, emissions are anticipated to be dropped 40 percent below 2018 levels, and by 2050, the country is expected to reach its required goal of being carbon-neutral [16–19]. But more than the existing measures will be needed to get us there. In 2019, Korea ranked seventh globally regarding carbon dioxide emissions, while the percentage of its energy produced from renewable sources was second lowest among OECD countries [20]. By coordinating its power sector transition with the Paris Agreement, South Korea can lay the groundwork for reaching its constitutionally mandated net zero emissions target by 2050 [21]. However, current policy recommendations must be revised to achieve this goal. Either South Korea can transition away from its reliance on fossil fuels, which will threaten its climate goals, raise air pollution, and intensify its dependence on imports, or it can keep doing what it has been doing. Based on projections from the International Energy Agency, the 9th Basic Plan implementation would drop the power industry’s carbon output to below 200 MtCO$_2$/yr by 2034 [22]. Furthermore, the proportion of worldwide emissions reductions that South Korea should be responsible for is higher than in economic-downscaled channels [23]. As a result, targeting the lower fifty percent of the carbon limit as an objective can assist South Korea in reaching its maximum potential ambition and aligning itself with the ideals of fairness and justice that lay at the core of the Paris Agreement. It is now more critical than ever for government officials to identify solutions to ecological degradation [24,25]. However, the OECD [26] notes that energy is vital to the functioning of many economic activities. This means that countries that want to keep their economies afloat but have a high energy intensity should switch to alternative sources of energy that produce less CO$_2$ and other pollutants. In this study, CO$_2$ emissions are analyzed concerning several economic and demographic variables and the use of fossil fuels and nuclear power as potential alternatives. In 2022, GDP growth was expected to be 2.7%; then, it is predicted to decelerate to 1.9%, 2.0%, and 1% in 2023 and 2024. Due to slow personal income growth and a stagnant property market, investments and private consumption are expected to slow down [27]. South Korea’s GDP in 2021 was estimated at USD 1798.53 billion. South Korea’s contribution to global GDP is 0.81 percent [28].

Already, a lot of movement is occurring in South Korean power industry policy. Recent years have seen a dramatic shift in the relative importance of fossil fuels, nuclear power, and renewable energy sources in the future of the electricity grid in reaction to technical and geopolitical changes. Amid all these shifts, however, a belief in the future importance of fossil gas has remained constant [29]. As a result, South Korean power sector emissions are anticipated to reach zero well before 2035.

The term “renewable energy” is used to describe power generated by resources that can be regenerated naturally, such as solar or wind power. In 2022, South Korea had 27.24 GW of renewable energy deployed, an enormous rise from the previous year’s figure of 24.36 GW and evidence of the nation’s growing utilization of green power. Under the
terms of the Paris Agreement from 2015, South Korea has committed to achieve a 37 percent drop in its CO₂ emissions by the year 2030. It was required that all of the power plants reduce their CO₂ emissions by 40% and 58% by 2022 and 2030, respectively, to achieve the goal [30]. Inversely correlated with CO₂, renewable energy is growing in popularity as a barometer of environmental health [31–33].

The use of fossil fuels is crucial to the South Korean energy industry. In 2021, coal was responsible for 35% of energy generation, while fossil gas accounted for another 30% [34]. During that period (2009–2013), the economy overgrew, pushing up the demand for fossil gas used to generate electricity. Even if the price of coal-fired energy fell and nuclear power plants resumed operations after being shut down for safety reasons in 2012, gas demand nonetheless dropped at an accelerated pace from 2013 to 2015 [35]. The design of the 10th Basic Plan for Electricity Supply and Demand was made public by the South Korean government in August of 2022. It is anticipated that by the year 2030, the ability to generate power from fossil fuels will have increased by forty percent and that fossil fuels will have accounted for twenty-one percent of all power production [29]. Furthermore, in December 2021, the government of the Republic of Korea stated that fossil gas power facilities that release emissions at levels less than 340 gCO₂/kWh would be provisionally recognized as green investments. The motivation behind this decision was to facilitate a shift away from energy powered by coal during the period when we are moving towards net zero [36].

The Ministry of Trade, Industry, and Energy (MOTIE) of South Korea projects that by 2036, nuclear energy will generate 34.6% of the country’s electricity, up from 27.4% in 2021. It is anticipated that the capacity of nuclear power plants to generate electricity will rise from their current level of 24.7 GW in 2022 to 28.9 GW in 2030 and then to 31.7 GW in 2036 [37]. Rising oil costs and other fossil fuels’ price volatility, increased reliance on imported energy, worries about the power grid’s reliability, and the effects of climate change have all contributed to nuclear power’s first prominence [38,39]. In addition, recent geopolitical events have brought to the forefront of global attention the significance of the reliability of energy and the indispensable part that nuclear power can play in providing clean and sustainable electricity [40].

In the specific context of South Korea, this study makes a pivotal contribution by comprehensively investigating the environmental ramifications of fossil fuels, renewable energy, and nuclear energy utilization through the application of the STIRPAT Model, coupled with advanced econometric techniques including ARDL, FMOLS, and CCR. This study’s significance emanates from its tailored analysis to the intricacies of South Korea’s energy landscape, reflecting the nation’s commitment to sustainable development.

By quantifying the multifaceted relationships between energy consumption and environmental outcomes, this research equips South Korean policymakers with empirically grounded insights. In a nation striving for economic growth while navigating environmental concerns, these findings offer a strategic foundation for formulating pragmatic energy and environmental policies. The incorporation of diverse energy sources aligns with South Korea’s ongoing efforts to diversify its energy portfolio, and the methodological rigor employed ensures the reliability of this study’s outcomes.

Furthermore, the acknowledgment of limitations and delineation of future research directions bespoke to the South Korean context underscores this study’s awareness of its own scope and the broader research landscape. This not only enhances the credibility of this study but also prompts a progressive discourse on energy–environment equilibrium among local researchers, policy circles, and stakeholders. Ultimately, this research extends beyond academia, facilitating informed decision making and fostering a sustainable trajectory for South Korea’s energy utilization and environmental preservation endeavors.

2. Literature Review

Numerous papers acknowledge the correlation between nuclear, renewable, and nonrenewable energy sources, GDP, population, and CO₂ emission. However, the research
is split into several sections based on how the variables listed below were initially predicted to interact.

2.1. Nexus between Renewable Energy, Nonrenewable Energy, and CO$_2$ Emission

Nuclear power has been acknowledged as a low-carbon transitional power-generating component to lessen the adverse environmental effects caused by burning fossil fuels. Nuclear power’s effect on the ecosystem was studied by Usman et al. [41], who applied the CS-ARDL procedure to 12 developed economies from 1980 to 2015. The statistical analysis reveals a strong negative association between the utilization of nuclear energy and ecological footprint. This finding supports the notion that the utilization of nuclear energy can contribute to environmental conservation by safeguarding natural resources as well as lessening carbon emissions. Pata and Samour [42] performed an analysis to look into the influence of nuclear power on ecology. Specifically, they investigated the extent to which nuclear energy contributed to the diminution in CO$_2$ emissions in France over the period spanning from 1977 to 2017. In their recent study, Ghosh et al. [43] employ innovative quantile regression methods to reveal the interplay between democracy, renewable energy consumption, and environmental quality across BRICS nations. This comprehensive analysis provides novel insights into the complex relationship between these factors, contributing to a deeper understanding of renewable energy and policy formulation. Voumik et al. [44] looked into the impact of renewable energy and nuclear energy on CO$_2$ emissions in EU countries from 1990 to 2021 and found that renewable energy decreased carbon output but nuclear energy had no impact on CO$_2$ emissions. Another study showed that fossil fuel accelerated ecological damage but nuclear power diminished it and renewable power had no impact on the environment in Italy from 1972 to 2021 [45]. Rahman et al. [46] found that fossil fuel boosted emission levels but renewable and nuclear power significantly lessened the carbon footprint in SAARC countries from 1972 to 2021. Pata and Samour [47] emphasized the significance of OECD nations prioritizing policies that promote the use of sources of clean energy. They argued that renewable energy not only enhances the load capacity factor but also contributes to long-term sustainability. As Hassan et al. [48] discovered that nuclear power plants significantly cut BRICS nations’ carbon footprints. Renewable energy mitigated carbon output in South Africa [49]. Energy efficiency and long-term economic viability necessitate expanding investments in nuclear power, as demonstrated by Lau et al. [50]. Jin [51] found that renewable power alleviated carbon output and made the environment more sustainable in OECD countries. Cleaner air is a direct result of using renewable energy, which is also the best way to reduce emissions caused by power plants [52–54]. It was found by Mujtaba et al. [55] that for every 1% boost in renewable energy, CO$_2$ emissions are reduced by 0.20%. Therefore, carbon dioxide emissions can be reduced by using renewable energy sources. If causative, using renewable energy produces a 1.2 percent lower carbon footprint per unit of energy consumed [56]. Hussain et al. [57] analyzed the impacts of energy mixing on CO$_2$ and found that renewable and nuclear power lowered emission levels. Still, fossil fuel and GDP boosted ecological deterioration by raising CO$_2$. Naimoglu [58] found that nuclear power alleviated carbon output. Attaining a green economy requires adequate support, which can be provided through green power and nuclear energy [59].

2.2. Nexus between GDP, Population, and CO$_2$ Emission

Sun et al. [60] revealed that expanding economic output and population were the main contributors to the high levels of pollution seen in the world’s most polluted countries. Rehueiro-Ferreira and Alonso-Fernandez [61] wrote that renewable power lessened the bad impact of carbon. Ihsan et al. [62] found that the GDP damaged ecological compatibility level through rising pollution. However, renewable energy and population growth help reduce emissions even as growing real incomes causes further environmental damage [63]. Cherni and Essaber [64] investigated how refillable energy and GDP determine CO$_2$ emis-
sions in Tunisia. The ARDL result concluded that GDP, carbon emissions, and refillable energy were stable for longer.

If the world quickly transitions from fossil fuels, lower outputs of glasshouse gases may offset the devastating impacts on the environment [65]. With their minimal carbon footprint and rapid scalability for widespread use, nuclear energy and renewable energy are realistic choices for meeting the world’s growing need for stable, trustworthy, and affordable power. Nuclear energy has the potential to assist in solving one of humanity’s most significant concerns, and this research will aid policymakers and government entities in grasping this. It is also essential to recognize that discussing renewable energy sources can help create a more sustainable world by reducing carbon dioxide emissions.

After analyzing the existing literature, this paper is crucial for the South Korean region because, recently, studies have not explored the impact of GDP, population, renewable energy, fossil fuel, and alternative nuclear energy on CO$_2$ emission. So, this paper will fill the existing literature gap by employing the widely used ARDL model. Also, for robustness, FMOLS and CCR will be employed.

3. Methodology

3.1. Theoretical Framework

This paper evaluates the impact of renewable energy, population dynamics, fossil fuel consumption, and alternative energy sources on carbon dioxide (CO$_2$) emissions in Korea, using statistical data spanning from 1972 to 2021. The STIRPAT framework, which is extensively employed, was utilized in this study. The STIRPAT paradigm is widely favored among academics due to its significance in addressing the challenges related to ecological impact. Initially, the IPAT equation was formalized to evaluate environmental impact. The IPAT equation was formulated by Ehrlich and Holdren [66] as well as Com-merner [67]. It represents a continuous link between population (P), income (A), and technology (T) in terms of environmental effect (I). The IPAT model is an initial endeavor to employ mathematical techniques in quantifying the ecological impacts resulting from human activity. The IPAT framework was originally developed by Ehrlich and Holdren [66,68], and subsequent research by these scholars led to the characterization of the equation as the multiplication of three distinct components [54]. The IPAT equation is formalized in Equation (1):

\[ I = \int \text{PAT} \]

In Equation (2), t is country, and \( \alpha, \gamma, \) and \( \varphi \) are the coefficients of P, A, and T, respectively.

\[ I = \beta P_t^\alpha \cdot A_t^\gamma \cdot T_t^\varphi \cdot \epsilon_t \]

In Equation (3), this paper presents a framework for analyzing the interplay between population, GDP, renewable energy, natural ecosystems, and fossil fuels regarding their impacts on CO$_2$ emissions.

\[ \text{CO}_2 = \int (\text{GDP, Population, Technologies}) \]

Nuclear power, fossil fuel, and renewable energy are employed as technology, as shown in Equation (4).
\[
\text{CO}_2 = \int (\text{GDP, POP, REN, FOS, ALNUC}) \tag{4}
\]

The accompanying Equation (5) displays the adjusted version of (4).

\[
\text{CO}_2t = \beta_0 + \beta_1 \text{GDP}_t + \beta_2 \text{POP}_t + \beta_3 \text{REN}_t + \beta_4 \text{FOS}_t + \beta_5 \text{ALNUC}_t + \epsilon_t \tag{5}
\]

The corresponding logarithmic expression is as follows:

\[
\text{LCO}_2t = \beta_0 + \beta_1 \text{LGDP}_t + \beta_2 \text{LPOP}_t + \beta_3 \text{LREN}_t + \beta_4 \text{LFOS}_t + \beta_5 \text{LALNUC}_t + \epsilon_t \tag{6}
\]

where LCO\textsubscript{2} is the logarithmic form of CO\textsubscript{2} emission at time t, LGDP\textsubscript{t} is the logarithmic form of GDP (per capita) at the time, LPOP\textsubscript{t} is the logarithmic form of the population, LREN\textsubscript{t} is renewable energy at time t, LFOS\textsubscript{t} is the logarithmic form of fossil fuel at time t, and LALNUC\textsubscript{t} is the logarithmic form of alternative nuclear power.

3.2. Data

Table 1 incorporates a list of the variables and their corresponding meanings and symbols implemented in this study. Specifically, the World Development Indicator serves as the basis for this analysis. This article uses numerous variables to assess the implications of South Korea’s GDP, population, fossil fuels, renewable energy, and nuclear power on the ecosystem.

Table 1. Definitions of variables, frequency, and sources.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Log Form</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2} emissions</td>
<td>LCO\textsubscript{2}</td>
<td>CO\textsubscript{2} emissions (kt)</td>
<td>World Bank Development Indicator [72]</td>
</tr>
<tr>
<td>Gross domestic product per capita</td>
<td>LGDP</td>
<td>GDP per capita (constant 2015 USD)</td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>LPOP</td>
<td>Population, total</td>
<td></td>
</tr>
<tr>
<td>Renewable energy consumption</td>
<td>LREN</td>
<td>Renewable energy consumption (% of total final energy consumption)</td>
<td></td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>LFOS</td>
<td>Fossil fuel energy consumption (% of total)</td>
<td></td>
</tr>
<tr>
<td>Alternative and nuclear energy</td>
<td>LALNUC</td>
<td>Alternative and nuclear energy (% of total energy use)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 demonstrates the summary analysis of this paper. The average mean value is the maximum in the population. The standard deviation confirms that fossil fuel and alternative nuclear energy fluctuate more than the other variables. Renewable energy has the minimum value, and the population has the maximum value.

Table 2. Summary Statistics.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>Standard Error</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCO\textsubscript{2}</td>
<td>13.05</td>
<td>0.199</td>
<td>12.42</td>
<td>13.35</td>
</tr>
<tr>
<td>LGDP</td>
<td>9.361</td>
<td>0.827</td>
<td>7.721</td>
<td>10.39</td>
</tr>
<tr>
<td>LPOP</td>
<td>17.61</td>
<td>0.129</td>
<td>17.33</td>
<td>17.76</td>
</tr>
<tr>
<td>LREN</td>
<td>0.124</td>
<td>0.588</td>
<td>-0.817</td>
<td>1.212</td>
</tr>
<tr>
<td>LFOS</td>
<td>4.477</td>
<td>0.0748</td>
<td>4.389</td>
<td>4.601</td>
</tr>
<tr>
<td>LALNUC</td>
<td>2.010</td>
<td>1.197</td>
<td>-0.824</td>
<td>2.917</td>
</tr>
</tbody>
</table>

Source: Authors’ calculation.

3.3. Econometric Methodology

3.3.1. Unit Root Test

The stationarity of the variables must be established before calculating the cointegration using the ARDL bounds test. To be stationary, a variable must have a constant
variance around its mean zero \([73,74]\). Time series variables typically exhibit nonstationarity. Regression using this method yields a fake information regression, which causes wrong estimation conclusions \([75,76]\). The ADF \([77–79]\), Kapetanios and Shin \([80]\), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) \([81]\) tests were performed as unit root tests to make sure the data were stationary. Under the assumption that the error terms are associated, the ADF test was used to conduct the time series unit root test. Tests for unit roots in the ADF test were performed using several different regression model parameters \([82,83]\):

For Model A, make sure there is no discernible trend or intercept:

\[
\Delta y_t = \gamma y_{t-1} + \sum P_i \Delta y_{t-i} + \epsilon_t
\]  

(7)

Model B: stationarity test (only the intercept is calculated).

\[
\Delta y_t = \mu + \gamma y_{t-1} + \sum P_i \Delta y_{t-i} + \epsilon_t
\]  

(8)

Model C: trend stationarity test (includes intercept and trend).

\[
\Delta y_t = \mu + \beta t + \gamma y_{t-1} + \sum P_i \Delta y_{t-i} + \epsilon_t
\]  

(9)

However, always, \(H_0: \gamma = 0\) in a unit root time series.

\(H_A: \gamma < 0\) in a stationary time series.

The KPSS test would be performed as a second check because there are discrepancies in the asymptotic distribution of the various unit roots.

### 3.3.2. Kwiatkowski, Phillips, Schmidt, and Shin’s (KPSS) Test

Suppose there is not convincing evidence to the contrary. In that case, the ADF test accepts the null hypothesis that the time series in question has a unit root, and this strategy may lack strength when up against stationary processes close to the unit root \([84]\). Kwiatkowski et al. \([81]\) offer an alternative test where the null hypothesis is that the series is stationary. The KPSS test is a valuable adjunct to the ADF test because it allows us to address questions about the reliability of either test by contrasting the statistical significance of the results. Even though it has significant drawbacks concerning the ADF and PP tests, the KPSS verifies the null hypothesis of stationarity \([85]\). The only two accessible models in KPSS are the following:

Model A: level stationarity testing (intercept only).

\[
y_t = \alpha_0 + \epsilon_t
\]  

(10)

Model B: trend stationarity test (includes trend and intercept in equation).

\[
y_t = \alpha_0 + \beta t + \epsilon_t
\]  

(11)

However, always, \(H_0: \sigma_u^2 = 0\) in a stationary time series.

\(H_A: \sigma_u^2 \neq 0\) in a nonstationary series.

### 3.3.3. KSUR Test

The KSUR testing approach is utilized in this paper because of its accuracy in modeling nonlinear and asymmetric behavior in time series. Unlike the linear unit root tests, the KSUR test performs better when significant disparities exist in the data \([86]\). Furthermore, compared to the initially proposed unit root test designed by Kapetanios et al. \([87]\), the KSUR test is more thorough because it incorporates additional criteria.

### 3.3.4. Unit Root Tests with Structural Break

Zivot and Andrews’s \([88]\) unit root test tests the structural break in time series data. It provides a reflective method to estimate the series’ discontinuity. It is figured as a single date of structural breakdown. Since the strength of unit root tests in time series analysis
would fluctuate without the presence of structural fractures, the Zivot–Andrews (ZA) procedure [88] is also performed [89]. As a result, ZA is used to stabilize the series and resolve the issue of its inconsistency.

3.3.5. ARDL Bound Test

To check if $\text{LCO}_2$, $\text{LGDP}$, $\text{LPOP}$, $\text{LREN}$, $\text{LFOS}$, and $\text{LALNUC}$ are cointegrated, we employ the ARDL bounds testing procedure, which is more reliable and efficient even with few data. Pesaran et al. [90] devised the ARDL limits testing approach, which examines the long-term association of variables without specifying whether they are I(0) or I(1) in advance or with a combination of orders of integration of I(0) and I(1). The benefits of this approach include the ability to simultaneously report on the long- and short-term movements of the configured model with the model used for error correction and to solve the issue of an unpredictable order of integration of series, provided that the series is of types I(0) and I(1) but not of I(2) [91].

Similarly, Fei et al. [92] and Johansen [93] showed that there is an expression for the ARDL bound test:

$$
\Delta \text{LCO}_2 t = \theta_0 + \sum_{i=1}^{t} \theta_1 \Delta \text{LCO}_{2-i} + \sum_{i=1}^{t} \theta_4 \Delta \text{LREN}_{t-i} + \sum_{i=1}^{t} \theta_5 \Delta \text{LFOS}_{t-i} + \sum_{i=1}^{t} \theta_6 \Delta \text{LALNUC}_{t-i} + \lambda_4 \text{LREN}_{t-1} + \lambda_3 \text{LFOS}_{t-1} + \lambda_6 \text{LALNUC}_{t-1} + \epsilon_t
$$

(12)

where $t$ is the lag size, $t - i$ is the optimal lags determined using the Akaike information criterion (AIC), $\epsilon_t$ is the error term, $\Delta$ is the first difference operator, and $\lambda$ analyzes the long-term correlation. With no cointegration and proof of cointegrations, both the null and alternate hypotheses are derived below.

$$
H_0 : \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = 0
$$

$$
H_1 : \lambda_1 \neq \lambda_2 \neq \lambda_3 \neq \lambda_4 \neq \lambda_5 \neq \lambda_6 \neq 0
$$

This joint significance test uses F-statistics to examine the possibility of cointegration between the variables under consideration. By rejecting the null hypothesis of no cointegration if the F-statistics value is more considerable than the upper critical value established by Pesaran et al. [94], we can infer that the variables are related over time. On the other hand, if the F-statistic is below the critical value, then the null hypothesis of cointegration is not rejected [95–97].

3.3.6. ARDL Model

The well-known ARDL technique was utilised to determine the effects, both long and short term. When the variables are fixed at the initial difference or the level, ARDL is a helpful method [98,99]. However, this method fails when variables are constant at the second difference. Compared to alternative ways of cointegration, the ARDL approach provides more benefits. The primary benefit of ARDL is its versatility; it may be used regardless of whether the underlying variables are stationary at zero, order one, or partial integration. Furthermore, not all variables are assumed to be in the same order. The ARDL method also has the added benefit of providing objective estimations of the model over the long term. In addition to these benefits, the ARDL method is also effective for limited sample sizes [100]. Furthermore, this method produces both long- and short-run coefficients, which can be utilized to infer beneficial policy outcomes. The ARDL method, in a similar spirit, incorporates a term for error correction that clarifies how immediate acts can have long-term consequences [101]. It was also found that the ARDL technique helps avoid problems brought on by using non-time series data [102,103].

The current study employed the ARDL testing methodology to delve deeper into the connection between CO$_2$ emissions and the analyzed regressors over the short and long term, as shown in Equation (13), which provides a representation of the ARDL testing model.
\[ \Delta \text{LCO}_{2\text{t}} = \theta_0 + \sum_{i=1}^{4} \theta_1 \Delta \text{LCO}_{2\text{t}-i} + \sum_{i=1}^{4} \theta_2 \Delta \text{LGDP}_{1\text{t}-i} + \sum_{i=1}^{4} \theta_3 \Delta \text{LPOP}_{1\text{t}-i} + \sum_{i=1}^{4} \theta_4 \Delta \text{LREN}_{1\text{t}-i} + \sum_{i=1}^{4} \theta_5 \Delta \text{LFOS}_{1\text{t}-i} + \sum_{i=1}^{4} \theta_6 \Delta \text{LALNUC}_{1\text{t}-i} + \lambda_1 \text{LCO}_{2\text{t}-1} + \lambda_2 \text{LGDP}_{1\text{t}-1} + \lambda_3 \text{LPOP}_{1\text{t}-1} + \lambda_4 \text{LREN}_{1\text{t}-1} + \lambda_5 \text{LFOS}_{1\text{t}-1} + \lambda_6 \text{LALNUC}_{1\text{t}-1} + \epsilon_t \] (13)

Adjustment pace is represented by the \( \theta_7 \) coefficient, the initials ECT indicate “error correction term”. \( t \) symbolizes time, and \( \epsilon_t \) is an error symbol. ECT\(_{1\text{t}-1} \) defines the error correction term of this model. There must be a negative and significantly low ECT value.

Parameter bias was avoided by first testing the estimated model for serial correlation, heteroskedasticity, model misspecification, and normality. The tests included the Breusch–Godfrey test [104], Ramsey’s RESET test [105], the Durbin–Watson test [106], and the Jarque–Bera test [107]. The problem of parameter bias was thus resolved. This action was taken to eliminate the possibility of parameter bias. Next, two metrics of model stability, the Cumulative Sum (CUSUM) and the Cumulative Sum (CUSUMSQ) of recursive residuals, were taken to ascertain the model’s resilience. These quantities are commonly referred to as CUSUM and CUSUMSQ [108].

3.3.7. Fully Modified Ordinary Least Squares

To combine the most accurate cointegration measures, Hansen and Phillips [109] developed FMOLS analysis. The FMOLS approach modifies the least squares method to account for the effects of cointegration on serial correlation and endogeneity in the explanatory factors. The polynomial regression of deterministic components, stationary error, and integrated processes no longer present as formidable a problem as they formerly did. The FMOLS test can shed light on the causal relationships between the investigated variables over a broad range of values [110,111]. The FMOLS test has various benefits since it helps validate what comes out of the cointegration test. Fixes for problems like autocorrelation and variance shift across and along dimensions are possible. Here, the constant term accounts for the possibility of a relationship between the error term differences and the explanatory variables [112]. The following equation is employed to measure the results of FMOLS and CCR.

\[ \Delta \text{LCO}_{2\text{t}} = \theta_0 + \sum_{i=1}^{4} \theta_1 \Delta \text{LCO}_{2\text{t}-i} + \sum_{i=1}^{4} \theta_2 \Delta \text{LGDP}_{1\text{t}-i} + \sum_{i=1}^{4} \theta_3 \Delta \text{LPOP}_{1\text{t}-i} + \sum_{i=1}^{4} \theta_4 \Delta \text{LREN}_{1\text{t}-i} + \sum_{i=1}^{4} \theta_5 \Delta \text{LFOS}_{1\text{t}-i} + \sum_{i=1}^{4} \theta_6 \Delta \text{LALNUC}_{1\text{t}-i} + \lambda_1 \text{LCO}_{2\text{t}-1} + \lambda_2 \text{LGDP}_{1\text{t}-1} + \lambda_3 \text{LPOP}_{1\text{t}-1} + \lambda_4 \text{LREN}_{1\text{t}-1} + \lambda_5 \text{LFOS}_{1\text{t}-1} + \lambda_6 \text{LALNUC}_{1\text{t}-1} + \epsilon_t \] (14)

3.3.8. Canonical Cointegrating Regression (CCR)

This study employs CCR as an alternative approach to calculate the coefficients. The conversion matrix regression (CCR) method was developed by Park [113] to correct errors in the least squares method by utilizing data transformed using the long-range covariance matrix. This modification attempts to eliminate the asymptotic internality that arises from long-range correlation [114]. It is comparable to FMOLS in many ways, especially in theory. The only real distinction is that it employs stationary data manipulations to mitigate the association between the cointegration equation and random shocks over the long term [113].

3.3.9. Granger Causality Test (GCT)

The condition where the independent variable’s past values are used appears more reliable than the condition where they are not used, according to the test proposed by Granger [115]. Granger causality test notation is included in Equations (15) and (16).

\[ X_t = \sum_{t=1}^{\rho} (a_{11,1} X_{t-1} + a_{12,1} Y_{t-1}) + \epsilon_t \] (15)

\[ Y_t = \sum_{t=1}^{\rho} (a_{21,1} X_{t-1} + a_{22,1} Y_{t-1}) + \xi_t \] (16)
where $\rho$ is the order of the model, $a_{ij}$ (i,j = 1,2) are the model’s coefficients, and $\epsilon_t$ and $\xi_t$ are the residuals. The coefficients can be estimated using the ordinary least squares method, and Granger causation between X and Y can be determined using F tests.

The Granger causality test is also used to investigate the relationship between LCO$_2$, LGDP, LPOP, LREN, LFOS, and LALNUC in the present study (Equations (17)–(22)). For the ECT, short-term changes in the series under investigation are isolated. Equations (17)–(22), depicting the EC-Model, can be seen here.

$$\Delta \text{LCO}_2 = \theta_0 + \sum_{i=1}^{4} \theta_i \Delta \text{LCO}_2 t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LGDP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LPOP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LREN} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LFOS} t-1 + \theta_7 \text{ECT} t-1 + \epsilon_{1t}$$  \hspace{1cm} (17)

$$\Delta \text{LGDP} = \theta_0 + \sum_{i=1}^{4} \theta_i \Delta \text{LGDP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LCO}_2 t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LPOP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LREN} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LFOS} t-1 + \theta_7 \text{ECT} t-1 + \epsilon_{1t}$$  \hspace{1cm} (18)

$$\Delta \text{LPOP} = \theta_0 + \sum_{i=1}^{4} \theta_i \Delta \text{LPOP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LCO}_2 t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LGDP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LREN} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LFOS} t-1 + \theta_7 \text{ECT} t-1 + \epsilon_{1t}$$  \hspace{1cm} (19)

$$\Delta \text{LREN} = \theta_0 + \sum_{i=1}^{4} \theta_i \Delta \text{LREN} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LCO}_2 t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LGDP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LPOP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LFOS} t-1 + \theta_7 \text{ECT} t-1 + \epsilon_{1t}$$  \hspace{1cm} (20)

$$\Delta \text{LFOS} = \theta_0 + \sum_{i=1}^{4} \theta_i \Delta \text{LFOS} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LCO}_2 t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LGDP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LPOP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LREN} t-1 + \theta_7 \text{ECT} t-1 + \epsilon_{1t}$$  \hspace{1cm} (21)

$$\Delta \text{LALNUC} = \theta_0 + \sum_{i=1}^{4} \theta_i \Delta \text{LALNUC} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LCO}_2 t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LGDP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LPOP} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LREN} t-1 + \sum_{i=1}^{4} \theta_i \Delta \text{LFOS} t-1 + \theta_7 \text{ECT} t-1 + \epsilon_{1t}$$  \hspace{1cm} (22)

The pairwise Granger causality testing hypotheses are the following:

$${H_0}: \text{Granger causality does not hold.}$$

$$H_1: \text{The null hypothesis is not true.}$$

This study applies the paired Granger causality testing strategy to investigate the possibility of causation to identify relatively short-term relationships between the components.

### 4. Results and Discussion

#### 4.1. Unit Root Test

Table 3 demonstrates the findings of the unit root test. This paper used the KSUR, ADF, and KPSS tests to examine the variables’ stationarity nature. The outcomes demonstrated that the LCO$_2$, LGDP, LPOP, and LFOS variables are stationary at first difference or I(1), whereas the LREN and LALNUC variables remain stationary at level or I(0), suggesting that these functions do not need to be differentiated to achieve stationarity.

#### Table 3. Unit root tests.

<table>
<thead>
<tr>
<th>Variable</th>
<th>KSUR Test</th>
<th>ADF Test</th>
<th>KPSS Test</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level</td>
<td>1st Diff.</td>
<td>Level</td>
<td>1st Diff.</td>
</tr>
<tr>
<td>LCO$_2$</td>
<td>-0.672</td>
<td>-4.387 ***</td>
<td>-0.055</td>
<td>-5.522 ***</td>
</tr>
<tr>
<td>LGDP</td>
<td>2.195</td>
<td>-3.380 ***</td>
<td>2.452</td>
<td>-3.531 ***</td>
</tr>
<tr>
<td>LPOP</td>
<td>2.684</td>
<td>-3.531 ***</td>
<td>2.195</td>
<td>-3.380 ***</td>
</tr>
<tr>
<td>LREN</td>
<td>-5.518 ***</td>
<td>-5.518 ***</td>
<td>-0.012</td>
<td>-6.051 ***</td>
</tr>
<tr>
<td>LFOS</td>
<td>-0.124</td>
<td>-6.051 ***</td>
<td>-0.052</td>
<td>-6.512 ***</td>
</tr>
<tr>
<td>LALNUC</td>
<td>-4.142 **</td>
<td>-4.056 ***</td>
<td>-4.584 **</td>
<td>-4.584 **</td>
</tr>
</tbody>
</table>

By using AIC and SIC, the length of the lag has been calculated. An intercept and a trend term are also included in all unit root testing. The estimated coefficients have significance levels of *** and ***, denoting statistical significance at 1% and 5%.
4.2. Unit Root with Structural Breaks

The outcomes of the Zivot–Andrews unit root test are outlined in Table 4. The ZA statistic is employed as a means of assessing the presence of a discontinuity within a time series. The ZA statistic of $-3.462^{***}$, which is statistically significant, confirms the presence of a structural break in the CO$_2$ emissions variable in the year 1990. The structural breakdowns of LGDP, LFOS, and LALNUC are also significant. According to the findings laid out, it can be observed that in the years 1990, 1983, 1985, and 1983, there were instances of significant shifts or disruptions in the patterns of CO$_2$ emissions, GDP, fossil fuel consumption, and nuclear energy utilization within the context of South Korea. Nevertheless, the remaining variables, namely LPOP and LREN, did not exhibit any significant structural discontinuities.

Table 4. Unit root with a structural break.

<table>
<thead>
<tr>
<th>Variables</th>
<th>ZA Statistic</th>
<th>Break</th>
<th>1%</th>
<th>5%</th>
<th>10%</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCO$_2$</td>
<td>$-3.462^{***}$</td>
<td>1990</td>
<td>$-5.34$</td>
<td>$-4.93$</td>
<td>$-4.58$</td>
<td>Break</td>
</tr>
<tr>
<td>LGDP</td>
<td>$-2.221^{***}$</td>
<td>1983</td>
<td>$-5.34$</td>
<td>$-4.93$</td>
<td>$-4.58$</td>
<td>Exist</td>
</tr>
<tr>
<td>LPOP</td>
<td>$-1.227$</td>
<td>1990</td>
<td>$-5.34$</td>
<td>$-4.93$</td>
<td>$-4.58$</td>
<td></td>
</tr>
<tr>
<td>LREN</td>
<td>$-5.568^{***}$</td>
<td>1991</td>
<td>$-5.34$</td>
<td>$-4.93$</td>
<td>$-4.58$</td>
<td></td>
</tr>
<tr>
<td>LFOS</td>
<td>$-4.706^{***}$</td>
<td>1985</td>
<td>$-5.34$</td>
<td>$-4.93$</td>
<td>$-4.58$</td>
<td></td>
</tr>
<tr>
<td>LALNUC</td>
<td>$-2.973^{***}$</td>
<td>1983</td>
<td>$-5.34$</td>
<td>$-4.93$</td>
<td>$-4.58$</td>
<td></td>
</tr>
</tbody>
</table>

Standard errors in parentheses $^{***}p<0.01$.

4.3. ARDL Bound Cointegration Test

The outcomes of the ARDL structural bound test are summarized in Table 5. In order to diagnose the long-term correlations between variables, we rely heavily on the bound cointegration test. This test establishes the presence of stable equilibrium linkages between GDP, population, fossil fuels, renewable energy, nuclear energy, and the environment in South Korea by discovering cointegration boundaries. With $K$ equal to 5, the F-statistic test statistic equals 1.721. The separate treatment of the I(0) and I(1) variables allows for critical value constraints at various significance levels. The essential bounds of value for I(0) are 2.26; for I(1), they are 3.35 at a 10% significance level. The critical value bounds are provided for both the 5% and 1% confidence intervals.

Table 5. Bound cointegration test.

<table>
<thead>
<tr>
<th>Test Statistic</th>
<th>Value</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-statistic</td>
<td>1.721</td>
<td>5</td>
</tr>
<tr>
<td>Significance level</td>
<td>Critical Value Bounds</td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>I(0)</td>
<td>2.26</td>
</tr>
<tr>
<td>5%</td>
<td>2.62</td>
<td>3.79</td>
</tr>
<tr>
<td>1%</td>
<td>3.41</td>
<td>4.18</td>
</tr>
</tbody>
</table>

4.4. ARDL Long- and Short-Run Results

The ARDL long-run and short-run results are demonstrated in Table 6. A positive association between GDP and CO$_2$ exists, and it is suggested that GDP brings about 0.268% CO$_2$ emission for every 1% rise in production capacity. But the coefficient is insignificant. Sun et al. [60] and Ihsan et al. [62] agreed with this finding. The population significantly exacerbated the ecological damage level through rising emissions, suggesting that the environmental deterioration level maximizes by 4.113% for 1% growth in the population. Guo et al. [116], Voumik et al. [117], Popescu [118], Popescu et al. [119], Nica et al. [120], and Rehman et al. [121] asserted these conclusions. The ecological compatibility level enhances using clean energy since a negative association exists between renewable
energy and CO₂ emission. It is demonstrated that CO₂ emission diminishes by 0.0853% for a 1% boost in the renewable usage level. Dogan et al. [49] and Mujtaba et al. [53] demonstrated that renewable energy cuts the carbon output. By contrast, fossil fuel and alternative nuclear power positively correlate with CO₂. Correspondingly, CO₂ emission rises by 2.558% and 0.286% for 1% rises in fossil fuel and nuclear energy. Hossain et al. [57] claimed that fossil fuel bumped up CO₂; by contrast, Sadiq et al. [47] and Rahman et al. [48] illustrated that nuclear energy decreased CO₂ emissions.

Table 6. ARDL long-run and short-run results.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Adjustment</th>
<th>Long Run</th>
<th>Short Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGDP</td>
<td>0.268 (0.479)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPOP</td>
<td>4.113 *** (2.029)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LREN</td>
<td>-0.0853 * (0.0430)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LFOS</td>
<td>2.558 (4.682)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LALNUC</td>
<td>0.286 (0.750)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.LCO₂</td>
<td>-0.618 *** (0.247)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.LGDP</td>
<td>0.586 * (0.318)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.LPOP</td>
<td>7.108 (4.312)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.LREN</td>
<td>0.0413 (0.0414)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.LFOS</td>
<td>-3.599 (3.490)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.LALNUC</td>
<td>-0.825 ** (0.395)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-46.04 * (25.18)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Standard errors in parentheses, *** p < 0.01, ** p < 0.05, * p < 0.1.

The short-term findings illustrate that GDP elevates ecological damage positively, demonstrating that 0.586% of carbon output is produced for every 1% of production. However, the population also stimulates climate damage, but the coefficient is insignificant. By contrast, fossil fuel improves ecological sustainability by 3.599% by lessening carbon production, but the coefficient is insignificant. Alternative nuclear energy also promotes environmental compatibility level, and it mitigates CO₂ by 46.04% for each 1% rise in the usage level of nuclear power.

The adjusted term indicates the negative and significant impact, and it is said that it will take almost two years to adjust in the long-run equilibrium.

4.5. Robustness Check

Table 7 displays the outcomes of tests to ensure the robustness of the FMOLS and CCR methods for the variables in this study. Coefficients and standard errors are given to provide an idea of the strength and relevance of the correlations. In accordance with the primary findings, the FMOLS coefficients for LGDP (gross domestic product per capita), LPOP (population), and LREN (renewable energy consumption) all point to the same conclusion: these variables have a substantial effect on the environment in South Korea. In this robustness analysis, however, neither LFOS (fossil fuels) nor LALNUC (alternative and nuclear energy) show statistically significant effects. The CCR method’s findings are also in line with this study’s core conclusions, which stress LREN’s major unfavorable effect on environmental pressures. There are no statistically significant associations between LGDP, LFOS, or LALNUC and the surrounding environment. The results of the robustness checks corroborate the primary findings by showing that the established connections hold up under repeated testing. Both the FMOLS and CCR models have very high R-squared values, indicating that they are able to account for a great deal of variation in the dependent variable. In general, the results of the robustness check back up the findings of the primary study, proving that South Korea’s environmental conditions are significantly influenced by the country’s GDP per capita, population, and consumption of renewable energy. These results have substantial repercussions for decision-makers and stakeholders in South Korea,
particularly with regards to the development of efficient strategies for sustainable energy planning and environmental management.

Table 7. Robustness check.

<table>
<thead>
<tr>
<th></th>
<th>FMOLS</th>
<th>CCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGDP</td>
<td>0.349 ** (0.169)</td>
<td>0.223 (0.224)</td>
</tr>
<tr>
<td>LPOP</td>
<td>3.473 *** (0.941)</td>
<td>4.196 *** (1.386)</td>
</tr>
<tr>
<td>LREN</td>
<td>−0.068 *** (0.018)</td>
<td>−0.075 *** (0.019)</td>
</tr>
<tr>
<td>LFOS</td>
<td>1.721 (1.248)</td>
<td>0.042 (2.569)</td>
</tr>
<tr>
<td>LALNUC</td>
<td>−0.028 (0.209)</td>
<td>−0.297 (0.422)</td>
</tr>
<tr>
<td>C</td>
<td>−59.337</td>
<td>−62.72</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.993</td>
<td>0.988</td>
</tr>
</tbody>
</table>

Standard errors in parentheses, *** $p < 0.01$ and ** $p < 0.05$.

4.6. Granger Causality

In Table 8, the Granger causality test reveals a unidirectional relationship between GDP and CO$_2$ emission, population to CO$_2$ emission, CO$_2$ to renewable energy, and fossil fuels to CO$_2$ emission. There is no bidirectional causality in the test.

Table 8. Granger causality test results.

<table>
<thead>
<tr>
<th>Pairwise Granger Causality Tests</th>
<th>Obs</th>
<th>F-Statistic</th>
<th>Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGDP does not Granger-cause LCO$_2$</td>
<td>48</td>
<td>4.44646</td>
<td>0.0428</td>
</tr>
<tr>
<td>LCO$_2$ does not Granger-cause LGDP</td>
<td>1.98205</td>
<td>0.1502</td>
<td></td>
</tr>
<tr>
<td>LPOP does not Granger-cause LCO$_2$</td>
<td>48</td>
<td>5.4933</td>
<td>0.0614</td>
</tr>
<tr>
<td>LCO$_2$ does not Granger-cause LPOP</td>
<td>1.79225</td>
<td>0.1788</td>
<td></td>
</tr>
<tr>
<td>LREN does not Granger-cause LCO$_2$</td>
<td>42</td>
<td>0.51766</td>
<td>0.6027</td>
</tr>
<tr>
<td>LCO$_2$ does not Granger-cause LREN</td>
<td>7.05747</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>LFOS does not Granger-cause LCO$_2$</td>
<td>42</td>
<td>6.3873</td>
<td>0.008</td>
</tr>
<tr>
<td>LCO$_2$ does not Granger-cause LFOS</td>
<td>1.02138</td>
<td>0.370</td>
<td></td>
</tr>
<tr>
<td>LALNUC does not Granger-cause LCO$_2$</td>
<td>42</td>
<td>0.03372</td>
<td>0.9669</td>
</tr>
<tr>
<td>LCO$_2$ does not Granger-cause LALNUC</td>
<td>0.1235</td>
<td>0.8842</td>
<td></td>
</tr>
</tbody>
</table>

4.7. Diagnostic Tests Results

Finally, the topic of the ARDL error correction model’s goodness of fit is discussed. A battery of diagnostic and stability tests was performed for this aim. Serial correlation, homoscedasticity, heteroscedasticity, normalcy, and model specification are all investigated by the diagnostic tests. Table 9 shows no problems with the model’s normality, heteroscedasticity, or higher-order autocorrelation. This elucidates the validity and trustworthiness of these research findings for concluding.

Figure 1 shows that the CUSUM and CUSUM squared values are consistent with a stable regression line. The line shows little to no fluctuation throughout the observation, demonstrating a steady connection. Evidence of the model’s reliability and support for the robustness of the findings are provided by the CUSUM and CUSUM square analyses. These numbers lend credence to the inference that the link between the variables is steady and can be used for future assumptions and choices.
Table 9. Residual diagnostic tests results of the ARDL models.

<table>
<thead>
<tr>
<th>Statistics Test</th>
<th>Null Hypothesis</th>
<th>Test Statistic</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AECH heteroskedasticity test</td>
<td>H₀: homoskedasticity</td>
<td>0.348</td>
<td>0.558</td>
</tr>
<tr>
<td>Normality/ Jarque–Bera</td>
<td>H₀: residuals are normally distributed</td>
<td>0.8745</td>
<td>0.5214</td>
</tr>
<tr>
<td>Breusch–Godfrey serial correlation LM test</td>
<td>H₀: no serial correlation up to 2 lags</td>
<td>1.916</td>
<td>0.170</td>
</tr>
<tr>
<td>R-squared</td>
<td></td>
<td></td>
<td>0.754</td>
</tr>
<tr>
<td>Adjusted R-squared</td>
<td></td>
<td></td>
<td>0.784</td>
</tr>
<tr>
<td>Durbin–Watson stat</td>
<td></td>
<td></td>
<td>1.762</td>
</tr>
<tr>
<td>Ramsey RESET test (F)</td>
<td>H₀: the functional form of the model is correct</td>
<td>3.192</td>
<td>0.086</td>
</tr>
</tbody>
</table>

Sources: the authors’ estimation.

Figure 1. CUSUM and CUSUM square tests.

5. Conclusions

This research used the STIRPAT model and the ARDL, FMOLS, and CCR techniques to analyze the effects of fossil fuels, renewable energy, and nuclear energy on the environment in South Korea. The ARDL findings provide essential insights into the connection between energy consumption patterns and environmental indicators. According to the data, population size in South Korea has a considerable effect on ecological pressures.

Our study confirms the findings of previous and other research by showing that rising GDP and population can lead to higher CO₂ emissions. In the case of South Korea, the increasing number of people has the highest detrimental impact on CO₂ emission, with a 4.113 *** coefficient. Switching to renewable energy, South Korea can cut down on CO₂ emissions. Renewable energy has been identified as a potential solution for controlling CO₂ emissions in Korea, as it exhibits a coefficient of −0.085 *. This indicates that growing populations contribute to worsening environmental conditions. The results from the FMOLS, CCR, and ARDL methods were consistent. According to FMOLS, GDP also has a notable effect on CO₂ emissions. This fact is also confirmed in studies by other authors [2,4]. While this study does show that renewable energy’s potential to minimize environmental consequences is promising, it also indicates that increasing the consumption of renewable energy has a considerable detrimental influence on ecological pressures.

6. Policy Recommendation

Further research and policy interventions are needed to evaluate the potential roles of fossil fuels and alternative/nuclear power in lowering environmental pressures, as these
energy sources did not substantially impact the environment in this study. However, the harmful impact of fossil fuels on the environment is presented in their studies by many authors, and in the case of Korea, the result would be similar [6–10]. In turn, the benefits and problems associated with nuclear energy require a detailed analysis. In the case of South Korea, energy is to be based on nuclear energy as a key tool for reducing emissions in the future, instead of solar, wind, or hydropower. Certainly, this will have a positive impact on the environment, but it is a completely different approach to changes in the energy policy compared to Western European countries, where nuclear energy is rather replaced by renewable energy [122–124]. In Europe, only Poland is an example of a country that intends to base its energy policy on nuclear energy by building small nuclear reactors.

Implications for sustainable energy planning and environmental management in South Korea are substantial in light of these findings. They stress the need for energy policies that encourage renewable energy and help achieve long-term sustainability. South Korea can help slow environmental degradation while boosting its economy if it prioritizes investments in renewable energy and takes steps to increase energy efficiency. Overall, the results of this study add to what is already known about how energy use affects the natural world. Moving towards a more sustainable and environmentally friendly energy system in South Korea, it offers evidence-based insights to aid policymakers in creating effective solutions.

7. Limitations and Future Research

The present study investigating the environmental impact of fossil fuels, renewable energy, and nuclear energy on South Korea’s environment through the STIRPAT Model, along with the ARDL, FMOLS, and CCR approaches, is subject to certain limitations. Firstly, this study’s outcomes heavily rely on the availability and accuracy of data, and any inaccuracies could potentially introduce bias into the results. Secondly, the assumptions of linearity and constant effects within the STIRPAT model may oversimplify the intricate dynamics of energy–environment relationships. Thirdly, the selection of variables could influence outcomes, possibly omitting relevant factors that contribute to environmental changes. Fourthly, the analysis establishes statistical correlations but does not definitively establish causation, leaving room for unaccounted confounding variables. Lastly, this study assumes a homogenous national impact, disregarding regional variations that might impact energy consumption and its consequences differently.

To address these limitations, future research should adopt more sophisticated methodologies. Longitudinal data could uncover gradual trends, while dynamic models might capture temporal nuances and feedback loops in energy–environment interactions. Exploring nonlinear relationships could shed light on threshold effects. Additionally, considering the influence of emerging energy technologies and potential policy shifts is crucial. Comparative studies across countries can offer valuable insights, and integrating qualitative analyses could provide a deeper understanding of influencing factors. Overall, more comprehensive and nuanced approaches are needed to advance our understanding of the intricate relationships between energy choices and environmental outcomes in South Korea.


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Data Availability Statement: The data will be available on request.

Conflicts of Interest: The authors declare no conflict of interest.
Abbreviations

ALNUC Alternative and nuclear energy
AIC Akaike information criteria
ARDL Autoregressive distributed lag model
ADF Augmented Dickey–Fuller
ANL Argonne National Laboratory
BRICS Brazil, Russia, India, China, and South Africa
CO₂ Carbon dioxide emission
CCR Canonical Cointegrating Regression
CUSUM Cumulative sum
CUSUMSQ Cumulative sum square
CS-ARDL Cross-sectionally Autoregressive Distributed Lag
FMOLS Fully Modified Ordinary Least Squares
FOS Fossil fuel
GDP Gross Domestic Product
GCT Granger causality test
GE General Electric Company
IPCC Intergovernmental Panel on Climate Change
IPAT Environmental impact (I) is the product of three factors: population (P), affluence (A), and technology (T)
KPSS Kwiatkowski–Phillips–Schmidt–Shin
LGDP Log of gross domestic product
LPOP Log of population
LREN Log of renewable energy
LFOS Log of fossil fuel
LALNUC Log of alternative and nuclear energy
MOTIE Ministry of Trade, Industry, and Energy
MSFR Molten salt fast reactor
NED Nuclear Energy Division
OECD Organization for Economic Cooperation and Development
POP population
PWR pressurized water reactor
REN Renewable energy
STIRPAT Stochastic impacts by regression on population, affluence, and technology
SAARC South Asian Association for Regional Cooperation
UN United Nations
ZA Test Zivot–Andrews Test

References


