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Original Article

Impact of nuclear and renewable energy sources on environment quality: Testing the EKC and LCC hypotheses for South Korea

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ABSTRACT

This study investigates the impacts of nuclear energy consumption on environmental quality from a different perspective by focusing on carbon dioxide (CO_2) emissions, ecological footprint, and load capacity factor. In this context, the South Korea case, which is a leading country producing and consuming nuclear energy, is investigated by considering also economic growth, and the 1997 Asian crisis from 1977 to 2018. To this end, the study employs the autoregressive distributed lag (ARDL) approach. Different from previous literature, this study proposes a load capacity curve (LCC) and tests the LCC and environmental Kuznets curve (EKC) hypotheses simultaneously. The analysis results reveal that (i) the LCC and EKC hypotheses are valid in South Korea; (ii) nuclear energy has an improving effect on the environmental quality; (iii) renewable energy does not have a significant long-term impact on the environment; (iv) the 1997 Asian crisis had an increasing effect on the load capacity factor; (v) South Korea has not yet reached the turning point, identified as $55,411, where per capita income improves environmental quality. Overall, the results show the validity of the LCC and EKC hypotheses and prove the positive contribution of nuclear energy to South Korea's green development strategies.

1. Introduction

Increasing air pollution has led to negative developments such as global warming, and climate change [1]. For this reason, environmental quality has become one of the most important aspects for countries and societies, while economic issues have also retained their importance. In line with this development, the current literature on environmental quality has recently expanded in search of ways to reduce greenhouse gas (GHG) emissions [2].

Most current studies use carbon dioxide (CO_2) emissions as a proxy for the quality of the environment and as a dependent variable in environmental analysis [3]. However, some recent researchers prefer a new environmental indicator such as the load capacity factor, which considers the biocapacity and ecological footprint (EF) of countries. Thus, it can be stated that the literature on environmental quality and its determinants has become more extensive.

In the previous literature, a high number of studies have focused on testing the EKC hypothesis proposed by Grossman and Krueger [4] while dealing with environmental quality. In these studies, CO_2 emissions and EF are often used as dependent variables, but the supply side of environmental problems is neglected. In ecological footprint accounting, EF components show human demand for natural resources, and biocapacity shows the supply of existing natural resources that can meet the demand. In this context, the load capacity factor (LCF) proposed by Siche et al. [5] and empirically analyzed for the first time by Pata [6], enables environmental assessment from both supply and demand perspectives.

The literature on LCF is growing but is not yet fully matured. The EKC hypothesis symbolizes an inverted U-shaped relationship between income and environmental degradation. This study not only tests the validity of the EKC hypothesis but also proposes a new curve, the Load Capacity Curve (LCC). Previous studies analyzing the determinants of LCF generally used linear models [7,8]. In contrast, this study indicates that there may be a U-shaped nonlinear link between LCF and income, and characterizes the U-shaped curve as LCC. The LCC curve is shown in Fig. 1.

The figure shows that as income increases, environmental quality (LCF) initially decreases, and above a certain income level, LCF increases with the development of environmental sensitivity and green technologies. This curve is the exact inverse of the EKC. The LCC hypothesis shows that increasing income can simultaneously affect biocapacity and EF. The LCC hypothesis assumes that in the early stages of economic development, environmental quality is severely compromised by fossil fuel use and anthropogenic activities without environmental concerns. However, when

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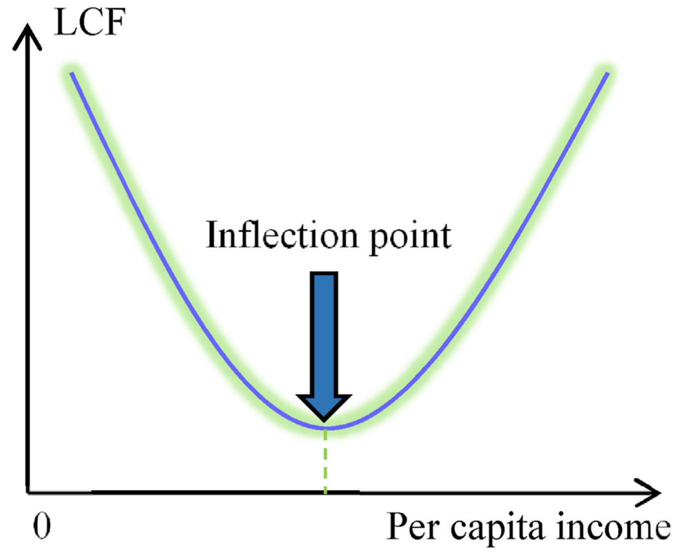

Fig. 1. Representation of the LCC hypothesis.

per capita income reaches a certain inflection point, people with increased income from that point consume more environmentally friendly products and use renewable energy sources, so environmental quality can be improved by reducing EF and increasing biocapacity. The study tests the validity of the LCC hypothesis by focusing on renewable and nuclear energy sources.

Coronavirus 2019 (COVID-19) has not only led to temporary reductions in environmental pollutants, such as particulate matter and nitrogen dioxide emissions [9,10] but also significant changes in the energy mix. For example, the share of nuclear energy in electricity generation in European Union member states decreased by 20% during COVID-19, while renewable resources increased by 9% [11]. However, in the next period, the energy crisis triggered by the tensions between Russia and Ukraine brought the increased use of nuclear energy to the agenda. The International Energy Agency (IEA), in its proposals to address the current energy crisis [12], has included increasing investment in nuclear power plant construction to boost nuclear power generation as a recommendation. Given the impact of the recent energy crisis and the IEA's recommendations, consideration of nuclear power as well as renewables in new environmental quality studies is imperative. Moreover, nuclear energy keeps nuclear materials inside while producing energy and does not use fossil fuels. Hence, it does not produce GHG emissions, which is an important advantage over fossil sources in terms of effects on environmental quality [13].

According to British Petroleum (BP), the highest nuclear energy power generating and consuming countries are the United States of America (USA), China, France, Russia, and South Korea, respectively [14]. These five countries generate and consume approximately 71% of the total nuclear energy in the world, so it might be useful to focus on one or some of these countries. In the current literature, several studies examine India, China, and France [6,8,15] in the context of nuclear energy. However, to date, there have been no studies analyzing the impact of nuclear energy consumption on environmental quality in South Korea. For this reason, a study on the South Korean case can further contribute to the literature. Fig. 2 Presents the progress trend of the environmental indicators in South Korea.

As Fig. 2 shows, EF has increased in South Korea, while biocapacity has steadily decreased. Because of this trend, the LCF of South Korea has decreased and it has been under a critical limit (i.e., 1). The LCF of South Korea per person was 0.48 in 1977 and 0.10 in 2018, and such a trend indicates that South Korea is facing a serious environmental problem. In the current literature, although some studies consider the LCF perspective, no study has yet comprehensively examined the South Korean case by considering the impact of nuclear energy on the LCF.

In summary, the literature on the LCF is growing, although the available studies are still limited. Some studies address the South Korean case, but no study examines the South Korean case in the context of LCF and nuclear energy in a single study. It is acknowledged that [17] uncover South Korea applying a quantile-on-quantile regression approach and does not include nuclear energy as an indicator. Therefore, new studies that examine South Korea in the LCF context by including nuclear energy comprehensively, using the most recent data, and adopting a novel approach can help fill the literature gap.

Considering the literature gap, the status of South Korea as one of the leading nuclear energy-consuming countries, and the potential contribution of nuclear energy consumption to environmental quality, this study investigates the effects of nuclear energy on environmental quality (measured by CO_2, EF, and LCF), while also controlling renewable energy, economic growth, and the 1997 Asian crisis. The objective of this study is to (i) establish the LCC hypothesis; (ii) test both the LCC and EKC hypotheses for South Korea; (iii) investigate the effect of nuclear energy on the LCF in South Korea, also considering renewable energy, economic growth, and the 1997 Asian crisis; (iv) define the inflection point to stimulate the positive contribution of per capita income to the LCF. The empirical results validate the LCC and EKC hypotheses, prove the contributing effect of nuclear energy on environmental quality, show how far away the inflection point is to stimulating the contribution of nuclear energy to environmental quality, and validate the robustness of the empirical results.

This study makes several contributions to the current literature. First, this study focuses on South Korean case as a leading nuclear energy-consuming country. While there are some articles on South Korea [e.g., 17], these studies do not address LCF and nuclear energy. Second, differently from most current studies, this study includes three environmental indicators (i.e., CO_2, EF, LCF) to investigate the proposed LCF hypothesis as well as the EKC hypothesis. Considering that, the literature about the LCF is growing but not yet mature, this study can be evaluated as one of the pioneer studies because it benefits from the South Korean example. Third, this study considers nuclear energy, renewable energy, economic growth, and the 1997 Asian crisis as explanatory variables in line with the current literature. Fourth, this study includes annual data for the period 1977–2018, which is the intersection of all variables. Therefore, it is thought that this study makes an important contribution to the current literature by focusing comprehensively on the South Korean example.

The remainder of the study consists of four sections. Section IIreviews the current literature. Section III presents data, model, and methodology. Section IV presents the empirical results. Section Vpresents the conclusions and policy recommendations.

2. A brief literature review

In the current literature, CO_2 emissions have been used intensively to examine the environmental quality of countries [e.g.,18]. With the increasing importance of environmental issues, EF began to be used in the literature [19]. More recently, LCF has been considered in limited studies [e.g., 20–24]. In considering the progress of environmental quality indicators on such a journey, three of these environmental quality indicators (i.e., CO_2, EF, LCF) are considered in this study to provide a clear picture of the examination.

A variety of factors has been used to examine environmental quality. Some recent studies consider renewable energy consumption. For instance Refs. [25–28], consider renewable energy when examining environmental quality. These studies conclude that renewable energy helps to limit pollution. However [29–31],

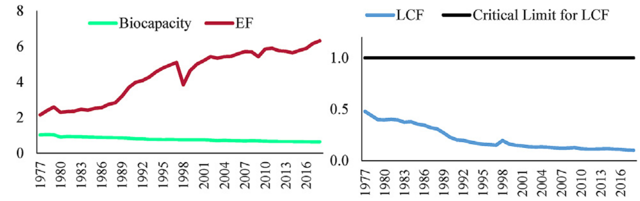

Fig. 2. Progress of environmental indicators in South Korea.
Source: Global Footprint Network [16].

argue that renewable resources in Vietnam, MENA countries, and China do not help prevent environmental degradation because they are not used effectively.

Several studies also use nuclear energy consumption as an environmental determinant. For example [3,8,15,32–34], use nuclear energy to examine the environmental quality of China, India, the top five carbon-emitting countries, Pakistan, the BRICS region, and France, respectively. These studies find that nuclear energy helps protect environmental quality by decreasing pollution. When searching the current literature for studies that include nuclear energy and the LCF, only [8], investigate nuclear energy in terms of its environmentally friendly role in France. Moreover, while there are numerous studies analyzing the EKC hypothesis [35], there is no study examining the LCC hypothesis.

Overall, it can be summarized that the current literature includes only a limited number of studies that address nuclear energy within the LCF concept in the same study, whereas the effect of renewable energy consumption and economic growth have been studied much more. In addition, some of the highest nuclear energy producing and consuming countries (i.e., the USA, France, China, and Russia) have been examined. The lack of a study in the literature examining the effects of nuclear power on environmental degradation in South Korea in the context of the LCF is a research gap. Therefore, this study aims to contribute to the current literature by focusing on South Korea in a comprehensive approach and providing implications for both nuclear energy-producing countries as well as those, who are considering the usage of nuclear energy as an option against energy crisis and environmental degradation problems.

3. Data, model, and methodology

3.1. Data and model

The study compiles annual data for the period 1977–2018 for South Korea from three different sources. According to Our World in Data [36], CO_2 represents carbon dioxide emissions (per capita, tons), REC denotes renewable energy consumption (per capita, kWh), and NEC symbolizes nuclear power consumption (per capita, kWh). Based on data obtained from the World Bank [37], GDP stands for the gross domestic product (per capita, constant 2015 dollars). Data are from Global Footprint Network [16], EF stands for ecological footprint (per capita, gha) and LCF is the load capacity factor (biocapacity/ecological footprint). Because the LCF includes biocapacity in the numerator and EF in the denominator, it allows for simultaneous environmental assessment on the supply and demand sides. A higher LCF indicates a better environment. Fig. 3 shows the progression of the analyzed variables over time in logarithmic form.

As can be seen in Fig. 3, EF has an upward trend, the LCF has been below the sustainability threshold for 40 years, GDP has increased over the years, REC has gained momentum after 2001, and the NEC has been on a steady trajectory since 2001.

The study uses three different models to analyze the LCC and EKC hypotheses. All variables are included in Equations (1)–(3) with logarithmic transformations to avoid the heteroscedasticity problem and to measure elasticities.

$$ln\,CO2_t = \rho_0 + \rho_1\, ln\,GDP_t + \rho_2\, ln\,GDPSQ_t + \rho_3 lnREC_t + \rho_4 lnNEC_t + e_t \quad (1)$$

$$ln\,EF_t = \tau_0 + \tau_1\, ln\,GDP_t + \tau_2\, ln\,GDPSQ_t + \tau_3 lnREC_t + \tau_4 lnNEC_t + u_t \quad (2)$$

$$ln\,LCF_t = \beta_0 + \beta_1\, ln\,GDP_t + \beta_2\, ln\,GDPSQ_t + \beta_3 lnREC_t + \beta_4 lnNEC_t + w_t \quad (3)$$

In these Equations., ρ_0, τ_0, and β_0 denote constant terms, $\rho_{1,2,3,4}$, $\tau_{1,2,3,4}$ and $\beta_{1,2,3,4}$ represent the elasticity corresponding to the relevant environmental indicator, and e_t, u_t, and w_t illustrate error terms. If the EKC hypothesis is valid, ρ_1 (τ_1) is positive, ρ_2 (τ_2) is negative, and both are statistically significant. Since LCF is an environmental quality indicator, the signs of income elasticities change place in the validity of the LCC hypothesis, and a U-shaped relationship is expected between income and environmental quality. In other words, for the validity of the LCC hypothesis, β_1 and β_2 should take negative and positive values, respectively, and at the same time be statistically significant.

Although some studies indicate that nuclear energy increases emissions (e.g., 38), researchers have emphasized the role of nuclear energy in promoting environmental quality in general [15,32–34]. Since South Korea is one of the world leaders in nuclear energy generation and consumption, ρ_4 and τ_4 are expected to be negative and β_4 is expected to be positive. While the environmental role of renewable energy is widely recognized [35], some studies claim that it does not affect environmental quality because renewable resources are not used sparingly and effectively [39]. Since renewable energy use and investment are quite limited in South Korea, ρ_3, τ_3 and β_3 are likely statistically insignificant.

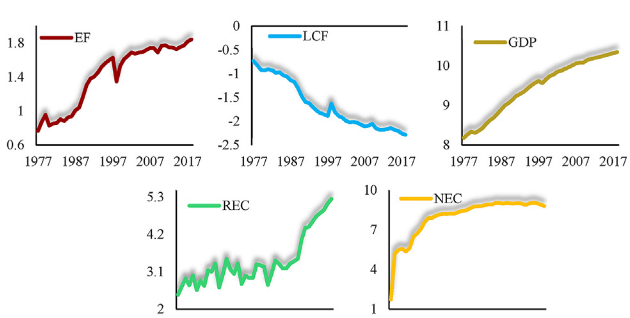

Fig. 3. Time series plots of the studied variables.

3.2. Methodology

The study uses the Autoregressive Distributed Lag Model (ARDL) and the combined cointegration test for the short- and long-term analysis of the cointegration relationship and the relationships between variables. The ARDL bounds test approach proposed by Pesaran et al. [40] allows simultaneous estimation of short- and long-run elasticities and permits the study of the cointegration relationship between series that have a different order of integration (I(0) or I(1) mix). Moreover, the ARDL approach gives effective results in samples with small observations. For the bounds test, the unrestricted error correction model (UECM) is set up in Equation (4), and the cointegration analysis is performed by applying the Wald test to the long-run coefficients.

$$\Delta ln\ EI_t = \vartheta_0 + \sum_{i=1}^{a} \vartheta_{1i} \Delta ln\ EI_{t-i} + \sum_{i=0}^{b} \vartheta_{2i} \Delta ln\ GDP_{t-i} + \sum_{i=0}^{c} \vartheta_{3i} \Delta ln\ GDPSQ_{t-i} + \sum_{i=0}^{d} \vartheta_{4i} \Delta ln\ REC_{t-i} + \sum_{i=0}^{e} \vartheta_{5i} \Delta ln\ NEC_{t-i} + +\mu_1\ ln\ EI_{t-1} + \mu_2\ ln\ GDP_{t-1} + \mu_3\ ln\ GDPSQ_{t-1} + \mu_4\ ln\ REC_{t-1} + \mu_5\ ln\ NEC_{t-1} + w_t \quad (4)$$

In Equation (4), ϑ_0 is the intercept, $\vartheta_{1,2,3,4,\text{and } 5}$ are the short run coefficients, $\mu_{1,2,3,4,\text{and } 5}$ are the long run coefficients, a, b, c, d, and e are the optimal lag lengths and w_t is the error term. For the test of the presence of cointegration, restrictions are applied to the constant term and the lags of the independent variables based on case II (restricted intercept and no trend). If the null hypothesis of no cointegration ($H_0 : \vartheta_0 = \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = 0$) is rejected, a long-run relationship is established, and then the short-run and long-run coefficients can be estimated based on the ARDL model.

In the study, the combined cointegration test of Bayer and Hanck [41] is used as another method (BH). Some cointegration tests may give different results. Therefore, Bayer and Hanck [41] developed a cointegration test that can provide more effective and meaningful results by combining the tests of Engle and Granger [42], Johansen [43] (JO), Boswijk [44] (BO), and Banerjee et al. [45] (BDM). The two statistics that can be measured for the BH cointegration test are shown in Equation (5).

$$EG\text{-}JOH = -2[\ln(p_{EG}) + \ln(p_{JOH})];\ EG\text{-}JOH\text{-}BO\text{-}BDM = -2[\ln(p_{EG}) + \ln(p_{JOH}) + \ln(p_{BO}) + \ln(p_{BDM})] \quad (5)$$

where, pEG, pJOH, pBO, and pBDM indicate the probability values of the above cointegration tests. EG-JOH is the combined version of only the first two tests, and EG-JOH-BO-BDM is the combined version of all four tests. In the Bayer-Hanck cointegration test, the probability values of these tests are combined using Fisher's [46] formula. If the calculated Fisher statistic is greater than the critical values, the null hypothesis of no cointegration can be rejected and the long-run relationship between the variables under study is established.

4. Empirical results

As a prerequisite for cointegration analysis in time series, the study uses various unit root tests to determine the degree of stationarity of the variables. The results of the Phillips and Perron [47] (PP) and Elliot et al. [48] Dickey Fuller-Generalised Least Squares (DF-GLS) unit root tests are shown in Table 1. The DF-GLS test results show that all variables contain a unit root in their levels and they become stationary at their first difference. Since the DF-GLS test produces more effective results for small samples, all variables are classified as I(1).

Having established that the variables are I(1), the optimal lag lengths for the Bayer-Hanck cointegration test are determined using various information criteria and presented in Table 2. According to the findings in the table, the optimal lag lengths for all three models are given as "3".

The results of the Bayer-Hanck cointegration test are presented in Table 3. The results show that the null hypothesis of no cointegration is rejected at the 1% level when CO_2, EF, and LCF are used as dependent variables. Thus, there is a long-term cointegration relationship between nuclear energy, renewable energy, income, and environmental indicators.

Table 4 presents the findings of the ARDL bounds test. A look at the diagnostic tests shows that all three ARDL models have no problems with autocorrelation, heteroscedasticity, non-normal distribution, and model specification. The F-statistic illustrates that the null hypothesis of non-cointegration is rejected for all three environmental indicators. These results are consistent with the combined cointegration test.

Having demonstrated the presence of cointegration, the study estimates the short- and long-term coefficients based on the ARDL method and presents them in Table 5. ECT_{t-1} ranges from 0 to −1 in all three models and is statistically significant. This suggests that the short-term deviations in environmental indicators will approach the long-term equilibrium value in about two years. Dummy97 represents the 1997 Asian crisis and causes a decline in EF. The decrease in production during the crisis contributes to an improvement in environmental quality, which is consistent with the outputs of Pata [27] and Pata [50], who found that the 2001 crisis in Turkey and the 2008 crisis in the United States reduced environmental degradation.

According to the long-term coefficients, the EKC hypothesis is valid for CO_2 and EF. There is an inverted U-shaped relationship between income level and these two environmental pollutants. Unlike the results of Baek [51], the results of our study are compatible with the EKC findings of Danish et al. [15], Dong et al. [32], Iwata et al. [52], and Lau et al. [53]. The watersheds, set at \$55,411-\$61,020, are higher than South Korea's per capita income of \$31,053 in 2018. In other words, South Korea has not yet reached the income level that would reduce environmental degradation. Our results also show that the newly proposed LCC hypothesis is valid because the GDP coefficient is negative, the GDPSQ coefficient is positive, and both are statistically significant. Previous studies in the literature have identified a monotonically increasing relationship between LCF and income [e.g., 7, 20]. In contrast, this study highlights that there is a U-shaped relationship between income and LCF.

Table 1
Results for unit root tests.

Variables	PP		DF-GLS	
	constant	constant + trend	constant	constant + trend
lnCO_2	−2.600 (1)	−0.635 (1)	0.256 (1)	−0.624 (0)
lnEF	−1.460 (3)	−1.636 (1)	0.017 (0)	−1.732 (0)
lnLCF	−1.653 (1)	−1.367 (1)	0.457 (0)	−1.390 (0)
lnGDP	−3.205 (1)**	0.097 (3)	−1.238 (5)	−0.188 (0)
lnREC	0.274 (6)	−1.779 (0)	0.126 (0)	−1.976 (0)
lnNEC	−7.057 (0)*	−6.260 (2)*	1.101 (1)	0.121 (1)
ΔlnCO_2	−5.283 (3)*	−5.956 (0)*	−5.182 (0)*	−6.100 (0)*
ΔlnEF	−7.185 (1)*	−7.186 (2)*	−5.943 (0)*	−7.026 (0)*
ΔlnLCF	−6.507 (1)*	−6.640 (1)*	−6.081 (0)*	−6.761 (0)*
ΔlnGDP	–	−5.785 (2)*	−4.387 (0)*	−5.937 (0)*
ΔlnREC	−8.974 (5)*	−10.470 (15)	−7.868 (0)*	−8.509 (0)*
ΔlnNEC	–	–	−1.475 (0)	−3.222 (0)**

Notes: The asterisks *, **, and *** represent significance at 1%, 5% and 10%, respectively. () indicates optimal lag lengths based on SBC For DF-GLS test and () shows Bandwidth for PP test.

Table 2
Optimal lag length selection for Bayer-Hanck cointegration test.

Dependent Variable	Lag	FPE	AIC	SC	HQ
CO_2	0	2.73e-07	−0.922	−0.709	−0.846
	1	1.37e-12	−13.142	−11.862	−12.683
	2	9.66e-13	−13.554	−11.208	−12.713
	3	8.32e-14*	−16.184*	−12.772*	−14.960*
EF	0	4.77e-07	−0.366	−0.153	−0.289
	1	1.99e-12	−12.768	−11.488	−12.308
	2	2.56e-12	−12.578	−10.232	−11.736
	3	2.42e-13*	−15.115*	−11.703*	−13.891*
LCF	0	5.73e-07	−0.182	0.030	−0.106
	1	2.42e-12	−12.571	−11.292	−12.112
	2	3.51e-12	−12.265	−9.919	−11.424
	3	3.02e-13*	−14.894*	−11.481*	−13.670*

Note: * is the value that minimizes the relevant information criterion.

Table 3
Results for combined cointegration.

Dependent Variable	EG-JOH	EG-JOH-BO-BDM	CV EG-J	CV EG-J-B-B	Conclusion
CO_2	18.300*	85.3190*	1%: 15.845	1%: 30.774	Cointegration
EF	56.132*	122.246*	5%: 10.576	5%: 20.143	Cointegration
LCF	56.917*	123.489*	10%: 8.301	10%: 15.938	Cointegration

Note: CV: Critical value.

Table 4
Results for ARDL bounds test.

k = 4	CO_2	EF	LCF
Dummy = 1997 Asian crisis	ARDL (2,1,1,2,2)	ARDL (1,1,1,0,2)	ARDL (1,1,1,0,0)
F-statistics	4.101**	6.829*	4.252**
Narayan [49] Table CV's	1%	5%	10%
I(0)	3.967	2.893	2.427
I(1)	5.455	4.000	3.395
Diagnostic check			
Ramsey-Reset	1.090 [0.306]	2.172 [0.151]	0.159 [0.692]
Jarque-Bera	1.109 [0.574]	0.486 [0.783]	0.345 [0.841]
White	0.780 [0.673]	1.788 [0.102]	1.593 [0.166]
ARCH	0.197 [0.659]	2.137 [0.152]	0.051 [0.820]
BG-LM	0.121 [0.885]	0.173 [0.841]	0.061 [0.940]
Dummy = 1997 Asian crisis			

Notes: The asterisk * and ** denote significance at 1% and 5% levels. [ ] indicates probability values.

Renewable energy has no long-term impact on environmental quality in terms of CO_2, EF, and LCF. The share of renewable energy in South Korea's total energy consumption is quite low at 3.18% [54]. Although South Korea would like to increase the share of renewable energy in total energy use to 7.7% by 2025, this is not possible with the current investment performance [55]. Renewable energy has not contributed economically and spatially in South Korea so far [56]. The results of our study show that renewable energy in South Korea also does not provide environmental benefits, and this result is consistent with the findings for various developing countries that cannot effectively use renewable energy sources [31,39].

Nuclear power is an effective policy tool to reduce CO_2 emissions and EF of South Korea and to increase LCF. The ARDL model results show that a 1% increase in nuclear energy consumption can reduce CO_2 emissions and EF by 0.22% and 0.19%, respectively, in the long run. At the same time, a similar increase could increase LCF by 0.24%. This finding for LCF is confirmed by Pata and Samour [8]. The corresponding results for CO_2 and EF are in line with [15,32–34, 57–59].

The stability of coefficients in ARDL models is analyzed using the CUSUM and CUSUM-SQ tests developed by Brown et al. [60] (see Appendix). According to Turner [61], the CUSUM test has stronger power properties than the CUSUMSQ test when the break is in the constant term. In this context, the coefficients in the EF model may also be stable because the CUSUM curve is within the 5% confidence interval. It can also be seen that the coefficients of the models for LCF and CO_2 are stable.

Finally, the study tests the robustness of the long-run coefficients and turning points using CCR and DOLS methods. The results of these methods presented in Table 6 are consistent with the ARDL coefficients.

5. Conclusion and policy recommendation

In this study, the validity of the Load Capacity Curve and Environmental Kuznets Curve hypotheses was examined simultaneously for the first time using various time series methods for the South Korean case. Also, the study introduced a new environmental policy approach to the literature by testing the LCC hypothesis. In this context, autoregressive distributed lag, canonical cointegrating regression, and dynamic ordinary least squares estimators were applied to analyze the impact of nuclear energy, renewable energy, and income on environmental indicators and to test the validity of the hypotheses.

The results of the analysis show that i) the hypotheses were confirmed. The minimum inflection points for carbon emissions and ecological footprint, where income could reduce environmental degradation, were found to be $48,202 and $49,690, respectively. For the load capacity factor, the minimum income level at which environmental quality begins to increase was set at $72,429. Since all of these watersheds are above South Korea's current income level, pollution continues to increase as the country's economy grows.

Table 5
Coefficients based on ARDL models.

Series	CO_2 coefficient	CO_2 probability	EF coefficient	EF probability	LCF coefficient	LCF probability
Long-run						
lnGDP	7.276*	0.001	5.299*	0.004	−5.670**	0.030
lnGDPSQ	−0.333*	0.003	−0.240**	0.010	0.249***	0.060
lnREC	0.011	0.726	−0.002	0.915	−0.030	0.542
lnNEC	−0.222*	0.003	−0.196*	0.003	0.244*	0.006
Dummy97	−0.115	0.195	−0.094**	0.035	0.060	0.363
Constant	−35.123*	0.000	−25.529**	0.031	27.696**	0.022
Inflection point	55,411$		61,020$		84,801$	
Short run						
$ln\Delta CO2_{t-1}$	0.126**	0.011	–	–	–	–
lnΔGDP	−3.262*	0.006	−7.875*	0.000	11.875*	0.000
$ln\Delta GDP_{t-1}$	–	–	−6.846*	0.004	–	–
lnΔGDPSQ	0.229*	0.000	0.494*	0.000	−0.722*	0.000
$ln\Delta GDPSQ_{t-1}$	–	–	0.366*	0.005	–	–
lnΔREC	0.018**	0.069	0.020	0.199	−0.041**	0.028
$ln\Delta REC_{t-1}$	0.019**	0.053	–	–	–	–
lnΔNEC	−0.097*	0.000	−0.053	0.140	0.095*	0.000
$ln\Delta NEC_{t-1}$	0.025*	0.000	0.043*	0.000	–	–
ΔDummy97	−0.079*	0.000	−0.142*	0.000	−0.001	0.987
ECT_{t-1}	−0.394*	0.011	−0.539*	0.000	−0.457*	0.000
Constant	−13.016*	0.000	−13.940*	0.000	11.931	0.000

Notes: The asterisks *, **, and *** represent significance at 1%, 5% and 10%, respectively.

Table 6
Robustness check for long-run estimation.

Model	CO_2		EF		LCF	
Series	coefficient	probability	coefficient	probability	coefficient	probability
DOLS						
lnGDP	8.067*	0.000	6.994*	0.004	−6.647*	0.000
lnGDPSQ	−0.374*	0.000	−0.323*	0.007	0.293*	0.000
lnREC	0.024	0.212	−0.033	0.247	0.034	0.154
lnNEC	−0.274*	0.000	−0.267*	0.003	0.262*	0.000
Constant	−38.543*	0.000	−33.396*	0.004	32.524*	0.000
Dummy97	−0.020	0.457	−0.064	0.138	0.071**	0.042
Inflection point	48,202$		49,690$		82,115$	
CCR						
lnGDP	8.406**	0.042	6.686*	0.004	−8.865*	0.006
lnGDPSQ	−0.388***	0.065	−0.301**	0.010	0.396**	0.015
lnREC	0.019	0.749	−0.066***	0.055	0.066	0.157
lnNEC	−0.307**	0.044	−0.318*	0.000	0.449*	0.001
Constant	−40.173**	0.035	−31.887*	0.003	42.664*	0.004
Dummy97	−0.029	0.660	−0.042	0.407	0.081	0.238
Inflection point	50,547$		65,351$		72,429$	

Carbon emissions and ecological footprint reductions will be possible in the coming years. To increase the load capacity factor, a higher income level is required than for the other two environmental indicators; (ii) as a result of the 1997 Asian crisis, pollution decreased due to a reduction in production; (iii) renewable energy does not play a role on environmental quality in the long term. The probable reason is the low and ineffective use of renewable energy in South Korea; (iv) nuclear energy is an energy source that can improve environmental quality in the long term according to empirical analyses for the three environmental indicators.

Several important policy recommendations emerge from the above findings. First, South Korea should implement greener economic development strategies, as it is far behind the watershed in preventing environmental degradation. Second, renewable energy is not an effective solution to South Korea's environmental problems. Therefore, policymakers should not devote too many resources to renewable energy, and efficiency in the use of available renewables should be improved. Third, investment in nuclear power plants should be increased because nuclear energy supports environmental quality. Nuclear energy is a cost-effective and stable resource. Since nuclear power is environmentally friendly, it could be a solution to South Korea's growing energy needs and help reduce dependence on energy imports. The replacement of nuclear energy with fossil fuels and the installation of new and technological reactors should be encouraged. In this context, the government can support nuclear energy through low tax policies and provide tax exemptions and incentives to facilitate the import of nuclear energy technologies by manufacturers. Policymakers should encourage domestic and foreign companies that offer nuclear energy to invest in green energy. Also, South Korea should increase the share of nuclear energy in electricity generation because of its importance on environmental quality.

Naturally, this study has some limitations, which are also research opportunities for future studies. Because this study analyzes the LCC and EKC hypotheses only for South Korea, future studies can test the validity of these hypotheses simultaneously for a group of countries by applying panel data methods. Similar countries can be also investigated in future studies. Moreover, some factors, such as the explosion risk of nuclear power plants, radiation risk, and potential health problems for workers and society, can be considered in future studies because they were not included in this study. Furthermore, various novel recent econometric approaches, such as rolling-windows causality and machine learning algorithms, can be applied in future studies to deepen the current knowledge. Thus, new studies can contribute to a better environmental assessment.

Disclosure statement

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Availability of data and materials

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Ethics approval and consent to participate

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Authors' contributions

The authors have contributed equally to this work. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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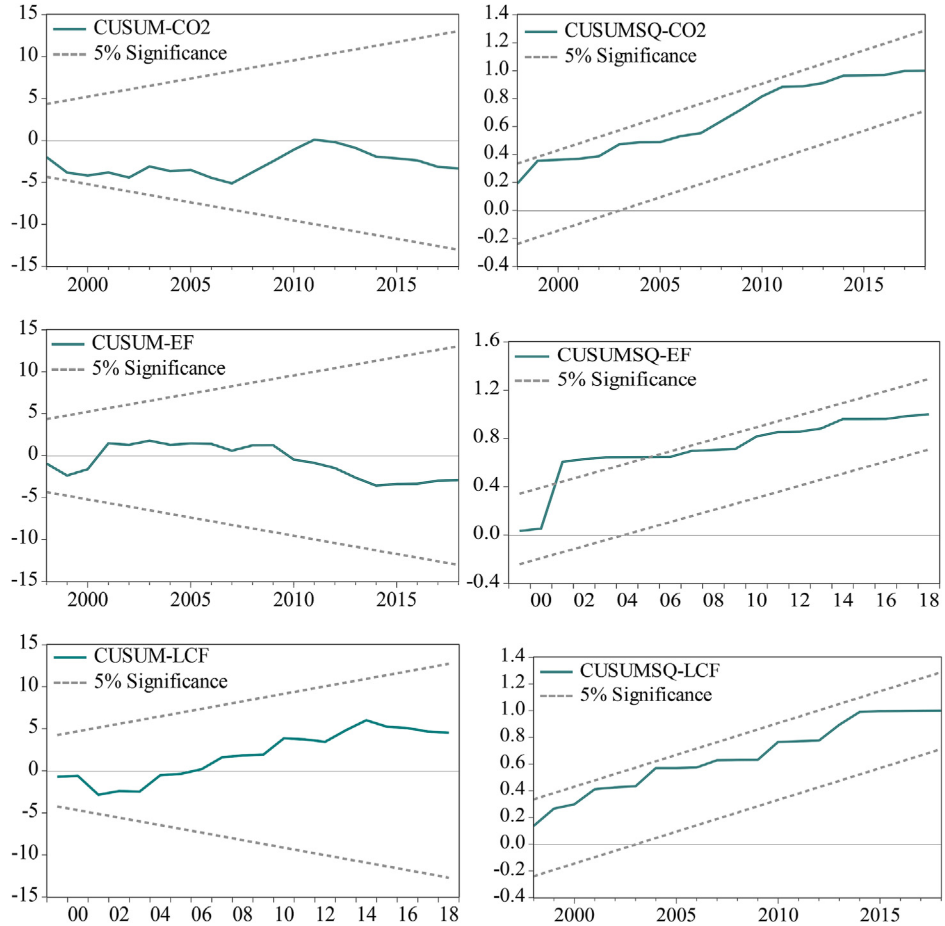
Appendix



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