Nuclear Energy, Economic Growth and Ecological Footprint in South Korea: An ARDL Approach (1990–2021)

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Abstract. South Korea possesses one of the world's most modern nuclear reactor fleets, and its "Green Deal" policy projects a significant expansion of nuclear energy capacity. In the aftermath of several significant nuclear accidents, public perception of nuclear energy technologies and facilities has emerged as a critical factor influencing national energy and electricity policymaking, particularly in countries that rely on nuclear power as a primary energy source. This study examines the interrelationships between energy, economic, and environmental factors specifically fuel energy structure, electricity generation from nuclear sources, GDP per capita, and ecological footprint from 1990 to 2021 using an Autoregressive Distributed Lag (ARDL) estimation model of South Korea. The findings reveal a stable long-run cointegration relationship among the variables. Crucially, nuclear energy deployment exhibits a significant negative long-run elasticity on ecological footprint, confirming its role in decarbonizing the energy sector.

Keywords: Environmental Kuznets Curve, ecological footprint, GDP, Electricity from nuclear.

1 Introduction

South Korea's rapid economic ascent since the 1960s, a phenomenon often termed “compressed development,” was fueled by a government-led strategy to secure energy that was both affordable and reliable. This policy triggered a monumental surge in electricity production, which skyrocketed from approximately 1.8 TWh in 1961 to 433 TWh in 2015 (Korea Electric Power Corporation, 2016). To power this growth, the nation established a generation mix dominated by coal and nuclear power. As of 2016, coal accounted for the largest share at 39.1%, followed by nuclear power at 30%, and liquefied natural gas (LNG) at 21.4% (Korea Electric Power Corporation, 2016).

South Korea's position on the Korean Peninsula prevents it from connecting with the Eurasian continent due to ongoing military tensions with North Korea. As a result, since the Korean War in 1950, the country has produced all its energy domestically, making a secure electricity supply its foremost policy priority. Although all energy resources must be imported, nuclear power plays a critical role in ensuring national energy security. Even though nuclear fuel is imported, its long fuel cycle and the sta-

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bility of long-term contracts (which often exceed 20 years) make it a uniquely reliable source of power for Korea.

The growing risks of climate change have intensified the global emphasis on transitioning to a low-carbon economy, a shift that signifies entry into a new climate regime. International efforts to mitigate these risks are embodied in key agreements such as the 1997 Kyoto Protocol and the 2015 Paris Agreement. Aligning with this global movement, South Korea has committed to reducing its greenhouse gas (GHG) emissions by 37% from business-as-usual (BAU) levels by 2030 (UNFCCC, 2016). Domestically, public support for low-carbon development is bolstered by tangible environmental concerns, as the expansion of coal-fired power plants and a surge in vehicle usage have significantly worsened the problem of fine dust.

Therefore, the relationship between environmental protection and economic development is a subject of academic debate, characterized by two contrasting perspectives. The first posits a trade-off, arguing that the two goals are inherently conflicting. This view is championed by neoclassical economic theory, which contends that stringent environmental regulations impose significant private costs on firms. These costs, the theory states, hinder productivity, erode market competitiveness, and ultimately stifle economic growth, despite the social benefits such protections may yield. Conversely, a second school of thought argues that economic and environmental objectives can be mutually reinforcing, which led us to the main question:

Does nuclear electricity generation contribute to reducing South Korea’s ecological footprint in the long run, after controlling for economic growth and fossil fuel consumption?

After citing our general problematic question, we tend to validate the following hypothesis:

H0: Fossil fuel energy consumption per capita has a significant strong impact on the ecological footprint in the long run.

H1: The relationship between GDP per capita and ecological footprint follows an inverted U-shape (the standard Environmental Kuznets Curve).

H2: An increase in electricity generation from nuclear sources leads to a significant reduction in the ecological footprint in the long run.

This study does not test the EKC hypothesis but focuses on the role of nuclear energy in mitigating environmental pressure.

2 Literature review

Addressing climate change and transitioning to a sustainable, low-carbon future demands global cooperation, especially in a world of finite resources. This transition yields significant secondary advantages beyond carbon reduction, commonly termed 'co-benefits.' These include enhanced air quality, gender empowerment, improved agricultural livelihoods, and local employment generation. For many communities, these co-benefits deliver immediate, tangible improvements in well-being and are often perceived as more directly beneficial than the abstract global goal of carbon mitigation. [1][2].

A persistent debate in academic circles centers on the tension between environmental regulation and economic growth. From the standpoint of conventional economics, a fundamental trade-off exists: stringent environmental protections are seen to impose higher costs on firms and dampen innovation, ultimately acting as a drag on economic advancement.

The complex interplay between human development, economic growth, and environmental sustainability is a central focus of contemporary academic and policy debates. While economic growth is instrumental in raising living standards, it often exacerbates environmental degradation, notably through increased greenhouse gas emissions. The central challenge, therefore, is to reconcile these objectives to achieve long-term sustainability a core imperative of the United Nations Sustainable Development Goals (SDGs).[3][4].

South Korea established a carbon emissions trading system (KETS) in 2015 as a key market-based instrument to manage and reduce greenhouse gas emissions. However, its inaugural year revealed significant challenges; a trading volume of only 1,190 tons represented less than 0.01% of the total allocated quota. This low participation highlighted persistent issues, including policy design flaws and high abatement costs. While the KETS, which was first legislated in 2011, remains an innovative practice for fostering green, low-carbon development, its initial effectiveness was limited. Furthermore, the nation's energy consumption, heavily reliant on fossil fuels like coal and oil, continues to pose a critical barrier to a sustainable low-carbon transition.

Despite global trade tensions and regional geopolitical challenges, South Korea's economy has exhibited notable resilience. Driven by robust exports and technological advancement, its economy grew at an average annual rate of 2.7% between 2013 and 2022, culminating in a 2.6% expansion in 2022. While this performance signified a solid recovery post-pandemic, it lagged behind the regional average of 4.4%. This economic progress, however, has been accompanied by significant environmental costs from decades of rapid industrialization. In 2022, South Korea was responsible for 1.6% of global CO_2 emissions from fuel combustion, with a total of 549.311 million metric tons a 32% increase since 2000 (IEA).

Sustainable development integrating economic growth, social well-being, and environmental protection poses a particular challenge for rapidly industrialized nations like South Korea. Despite its significant economic and human development achievements, the country's rising carbon emissions raise concerns about the long-term sustainability of its growth model. This context warrants an examination of the long-run relationship between human development, economic growth, and per capita carbon emissions to address the critical question of how to reconcile development aspirations with planetary boundaries. [1][5][6].

The theoretical framework of this study draws upon the Environmental Kuznets Curve (EKC) hypothesis initially developed by Grossman and Krueger, which posits a non-linear relationship between economic growth and environmental degradation. The EKC framework identifies three core mechanisms: the scale effect (where economic expansion increases environmental pressure), the composition effect (structural shifts in the economy that may alter pollution intensity), and the technique effect (technological improvements that enhance environmental efficiency). In this study, GDP per capita and its squared term are included to test for potential non-linearity. However, the estimated coefficients indicate a U-shaped relationship rather than the traditional inverted U-shape predicted by the EKC. This suggests that environmental pressure initially decreases with income growth but begins to rise again beyond a certain income threshold. The calculated turning point must therefore be interpreted cautiously, as it does not confirm the standard EKC mechanism. Instead, the results imply that the scale effect may currently dominate technological and structural improvements in South Korea. Within this framework, nuclear energy is examined as a decarbonization channel capable of mitigating environmental pressure by counteracting fossil fuel dependence.

In addition, the theoretical foundation of the Environmental Kuznets Curve (EKC) rests on two core mechanisms. The first is the income elasticity of environmental demand: as incomes rise, individuals prioritize quality of life, increasing their demand for environmental amenities and healthier products. This shift in public preference pressures governments to enact stricter environmental regulations, thereby improving overall environmental standards. This dynamic is widely cited in EKC literature as a key driver in pollution reduction.

The second mechanism involves the composite effects of economic growth, as conceptualized by Grossman and Krueger. They posit three distinct channels:

-The scale effect: Expanding economic output increases resource consumption and pollution, degrading environmental quality.

-The structural effect: Economic development triggers a sectoral shift (e.g., from manufacturing to services), which can alter environmental impacts.

-The technical effect: Rising incomes and technological progress facilitate the adoption of cleaner, more efficient technologies, enhancing environmental quality.

The EKC's inverted U-shape emerges as the positive structural and technical effects, which intensify with development, eventually overcome the initial negative scale effect. Consequently, environmental degradation increases in the early stages of growth but diminishes after a certain income threshold is reached.

The hypothesis links income per capita with environmental degradation, the ecological footprint is defined as the total area of productive land and water ecosystems required to produce the resources a population consumes and assimilate its waste. It is widely praised as an effective heuristic tool, translating complex resource use into a single, easily understood metric: the equivalent land area. This aggregating power is the EF's primary strength, facilitating straightforward decision-making by distilling multifaceted environmental data into one number. However, this very strength is also a source of controversy, particularly when the ecological footprint is interpreted as a direct indicator of biophysical limits and sustainability. A key drawback of such aggregate indicators is that they can obscure the underlying data, assumptions, and uncertainties, risking misinterpretation if users are not sufficiently informed.[7][8][9].

This study does not test the EKC hypothesis but focuses on the role of nuclear energy in mitigating environmental pressure, such as low-carbon power generation is primarily derived from two sources: renewables and nuclear energy. Renewable sources such as solar, wind, biomass, and geothermal are characterized by their continuous replenishment. Despite rapid growth in adoption, they currently constitute a minor share of the global energy mix, meeting approximately 14% of total demand and representing only about 3% of primary energy consumption. Projections, however, indicate a substantial increase, with their global share expected to reach 30–80% by 2100. In contrast, nuclear energy, which provides roughly 20% of the world's electricity, experienced a resurgence from the mid-2000s until the 2011 Fukushima incident, driven by growing climate concerns over fossil fuels.

The global energy landscape is in a state of flux, shaped by transformative events like North America's shale revolution and Japan's Fukushima nuclear disaster. This instability highlights the complex interplay between the pursuit of sustainable energy and the immediate, everyday risks associated with all power sources, ranging from electrical failures to gas-related accidents. Consequently, energy safety has become an unavoidable and critical priority. This reality was clearly demonstrated during Korea’s 2013 electricity shortage, which served as a national warning that supply–demand challenges are intensifying in both frequency and severity.Since the commissioning of its first nuclear power reactor in 1978, South Korea has developed one of the world's most substantial nuclear energy programs. Over the past three decades, the country has built 26 reactors, 25 of which are currently operational with a peak capacity of 23.78 GWe. Nuclear power's contribution to the national grid has surged by over 26% to 165 TWh, positioning South Korea among the globe's most nuclear-dependent nations. This strategic reliance stems from a national consensus; successive governments have consistently endorsed nuclear energy as a cornerstone of electricity supply, a necessity driven by limited domestic energy resources and escalating industrial demand.[1][10][11][12].

Nuclear energy plays a critical role in global electricity security and decarbonization by providing a stable, dispatchable power source that helps balance grid supply and demand. Accounting for nearly 10% of global electricity generation and roughly 20% in developed countries nuclear power offers a technically robust pathway to reduce fossil fuel dependence and meet stringent climate targets. This potential is recognized internationally; at the COP-28 summit, over twenty nations, including South Korea, pledged to triple global nuclear capacity by 2050 to achieve net-zero GHG emissions by mid-century and keep the 1.5°C target within reach. As the world's fifth-largest nuclear power producer, with 26% of its electricity derived from nuclear sources, South Korea exemplifies this strategy. Like many industrialized nations, its socio-economic advancement is deeply tied to reliable and substantial energy provision, in which nuclear power is a crucial component.[10][13][14][15][16].

3 Empirical study:

To answer our main question:Does nuclear electricity generation contribute to reducing South Korea’s ecological footprint in the long run, after controlling for economic growth and fossil fuel consumption?

this study employs an Autoregressive Distributed Lag (ARDL) model. The empirical analysis, covering the period 1990–2021, utilizes the following variables, presented in table 1, to examine the dynamic relationships between economic, energy, and environmental indicators:

Table 1:the variables of the research

Variable	Unit	source
Electricity from nuclear	TWH	our world data
Ecological footprint	GHA	ecological footprint network
GDP PER CAPITA	US $	world bank
Fossil fuel consumption- Gas per capita	(kWh)	our world data

Source 1: by Authors.

The ecological footprint is used as a broad environmental pressure indicator. Results should therefore be interpreted as overall environmental stress rather than pure carbon emissions, and due to data consistency and degrees of freedom constraints, fossil fuel consumption is proxied by gas consumption per capita, which represents a cleaner fossil energy source in Korea's energy mix.

3.1 Unit Root Test:

To determine the order of integration for each variable in table 1, we employ both the Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) unit root tests. These tests examine whether the series are stationary in their levels or require first differencing to achieve stationarity. The results of these tests, including the test statistics and critical values, are presented in Table 2 below.

Table 2: ADF&PP

Variables	**ADF**			**PP**		
	Intercept	**Intercept & Trend**	**No Intercept & Trend**	**Intercept**	**Intercept & Trend**	**No Intercept & Trend**
	Level					
lnEF	-1.414291 (0.5625)	-2.425809 (0.3601)	0.713134 (0.8640)	-1.325639 (0.6049)	-2.142435 (0.5032)	1.901143 (0.9841)
lnELN	-2.619160* (0.0004)	-6.417494 (0.0000)	-2.272598 (0.0247)	-2.619160* (0.0004)	-6.384546 (0.0001)	-2.490763 (0.0145)
lnGDP	-1.372849 (0.5825)	-2.865348 (0.1867)	2.348691 (0.9942)	-1.475060 (0.5327)	-2.873157 (0.1843)	3.624243 (0.9998)
LnGDP2	-1.241290	-2.851673	2.325698 (0.9939)	-1.300240	-2.866208	3.596425

Variables	ADF			PP		
	Intercept	**Intercept & Trend**	**No Intercept & Trend**	**Intercept**	**Intercept & Trend**	**No Intercept & Trend**
	(0.6435)	(0.1910)		(0.6168)	(0.1864)	(0.9998)
lnFF	-2.829541 (0.0658)	-4.588113 (0.0048)	0.336807 (0.7761)	-2.642618 (0.0956)	-4.611654 (0.0046)	0.648764 (0.8510)
	First Differences					
lnEF	-3.679322*** (0.0001)	-4.309824*** (0.0005)	-2.644302*** (0.0000)	-3.670170*** (0.0000)	-4.296729*** (0.0000)	-2.644302*** (0.0000)
lnELN	-3.689194*** (0.0000)	-3.580623** (0.0000)	-2.650145*** (0.0000)	-3.670170*** (0.0001)	-4.296729*** (0.0000)	-2.644302*** (0.0000)
lnGDP	-2.967767** (0.0004)	-4.948181 (0.0022)	-1.952473** (0.0000)	-2.963972** (0.000)	-6.807496 (0.0000)	-1.952473** (0.0000)
lnGDP2	-2.967767** (0.0003)	-4.991299 (0.0020)	-1.952473** (0.0001)	-2.963972** (0.0000)	-6.630914 (0.0000)	-1.952473** (0.0001)
lnFF	-3.670170*** (0.0000)	-4.296729*** (0.0000)	-2.644302*** (0.0000)	-3.670170*** (0.0000)	-4.296729*** (0.0000)	-2.644302*** (0.0000)

Notes: ( ) P-value; * Significant at 10%; ** Significant at 5%; *** Significant at 1%.

Source 2: Authors by eviews10.

Table 2 presents the results of the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests. At levels, most variables (lnEF, lnGDP, and $\ln GDP^2$) fail to reject the null hypothesis of a unit root, indicating non-stationarity. Although lnELN and lnFF show partial significance under certain specifications, the overall evidence suggests that the variables are non-stationary in level form.

After first differencing, all variables become statistically significant at conventional levels under both ADF and PP tests. This confirms that the series are integrated of order one, I(1).

Since none of the variables are integrated of order two, the ARDL bounds testing approach is appropriate for examining the existence of a long-run relationship among the variables.

3.2 ARDL short run estimation:

The short-run specification captures the immediate effects of changes in nuclear electricity generation, fossil fuel consumption, and economic growth on the ecological footprint. These dynamic adjustments reflect temporary deviations from the long-run equilibrium and provide insight into the speed and direction of short-term responses. While short-run coefficients indicate immediate impacts, greater emphasis is placed on the long-run relationship for policy interpretation.

Table 3: short run estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LNEF(-1)	0.629520	0.197077	3.194282	0.0495
LNEF(-2)	-0.926723	0.310490	-2.984711	0.0584
LNEF(-3)	0.411250	0.298838	1.376164	0.2625
LNEF(-4)	-0.264346	0.278645	-0.948685	0.4128
LNELECTRICITY_FROM_NUCLEAR___TWH	-0.188076	0.058273	-3.227518	0.0483
LNELECTRICITY_FROM_NUCLEAR___TWH(-1)	-0.098001	0.027724	-3.534910	0.0385
LNELECTRICITY_FROM_NUCLEAR___TWH(-2)	-0.009898	0.020525	-0.482224	0.6626
LNELECTRICITY_FROM_NUCLEAR___TWH(-3)	-0.080503	0.020108	-4.003473	0.0279
LNELECTRICITY_FROM_NUCLEAR___TWH(-4)	0.048581	0.028078	1.730206	0.1820
LNGAS_PER_CAPITA__KWH_	0.120181	0.074989	1.602655	0.2073
LNGAS_PER_CAPITA__KWH_(-1)	0.093673	0.059584	1.572116	0.2140
LNGAS_PER_CAPITA__KWH_(-2)	0.003539	0.043250	0.081817	0.9399
LNGAS_PER_CAPITA__KWH_(-3)	0.128874	0.048996	2.630293	0.0783
LNGAS_PER_CAPITA__KWH_(-4)	-0.069028	0.038708	-1.783301	0.1725
LNGDPC	11.58407	6.068484	1.908891	0.1523
LNGDPC(-1)	-16.79391	8.151628	-2.060191	0.1315
LNGDPC(-2)	16.00916	9.693733	1.651496	0.1972
LNGDPC(-3)	-12.50953	9.709248	-1.288414	0.2880
LNGDPC(-4)	-26.37304	10.70588	-2.463416	0.0906
LNGDPC2	-0.608932	0.327117	-1.861514	0.1596
LNGDPC2(-1)	0.855657	0.435337	1.965502	0.1441
LNGDPC2(-2)	-0.833157	0.520014	-1.602182	0.2074
LNGDPC2(-3)	0.6643	0.523	1.2697	0.2937

	50	224	24	
LNGDPC2(-4)	1.356345	0.562205	2.412545	0.0948
C	151.1394	47.60283	3.175010	0.0503

R-squared	0.987100	Mean dependent var	12.79746
Adjusted R-squared	0.883902	S.D. dependent var	0.199682
S.E. of regression	0.068038	Akaike info criterion	-2.985378
Sum squared resid	0.013888	Schwarz criterion	-1.795910
Log likelihood	66.79529	Hannan-Quinn criter.	-2.621746
F-statistic	9.565085	Durbin-Watson stat	1.562577
Prob(F-statistic)	0.043388		

Source 3: Authors by eviews10.

The results, presented in table 3, show strong persistence in the ecological footprint, as several lagged values of lnEF are significant. Nuclear electricity generation has a negative and statistically significant short-run effect in multiple lags, indicating its role in reducing environmental pressure.

Gas consumption shows mostly insignificant short-run effects, suggesting limited immediate impact. Economic growth and its squared term display unstable and largely insignificant coefficients, providing no clear short-run nonlinear pattern.

3.3 ARDL long run estimation:

Following the confirmation of cointegration, the long-run ARDL estimates capture the equilibrium relationship between ecological footprint, nuclear electricity generation, fossil fuel consumption, and economic growth. Unlike short-run dynamics, the long-run coefficients reflect the sustained and structural effects of these variables on environmental pressure. These results, shown in table 4, are central for policy interpretation, as they indicate whether changes in the energy mix and economic activity have permanent environmental implications.

Table 4: long run estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LNELECTRICITY_FROM_NUCLEAR___T	-	0.0718	-	0.028

WH	0.285054	11	3.969498	6
LNGAS_PER_CAPITA__KWH_	0.241015	0.107250	2.247228	0.1102
LNGDPC	-24.41386	5.914335	-4.127913	0.0258
LNGDPC2	1.246860	0.295189	4.223933	0.0243
C	131.3914	29.13878	4.509160	0.0204

Source 4: Authors by eviews10

Table 4 presents the estimated long-run coefficients from the ARDL model. **Nuclear electricity consumption** has a negative and significant coefficient (-0.285, p<0.05), indicating that a 1% increase reduces ecological footprint by 0.28% in the long run.**Natural gas consumption** is positive but insignificant (0.241, p>0.10), suggesting no clear long-run impact.**GDP per capita** is negative and significant (-24.414, p<0.05), while **GDP per capita squared** is positive and significant (1.247, p<0.05). This confirms an Environmental Kuznets Curve (EKC) relationship, though U-shaped: ecological footprint decreases at early income stages but increases after a certain threshold.

3.4 The Bound test:

The **Bounds Test** (Pesaran et al., 2001) is an econometric method used to test for a long-run relationship between variables regardless of whether they are stationary (I(0)) or integrated of order one (I(1)). It relies on the ARDL framework, allowing flexibility in variable integration and is especially useful for small samples, providing critical value bounds to determine the existence of cointegration.

Table 5: F-bound test

Test Statistic	Value	Signif.	I(0)	I(1)
			Asymptotic: n=1000	
F-statistic	5.362614	10%	2.2	3.09
k	4	5%	2.56	3.49
		2.5%	2.88	3.87
		1%	3.29	4.37

Source 5: Authors by Eviews10.

The bounds test, presented in table 5, yields an F-statistic of **5.363**, which exceeds the upper critical bound at the **1% (4.37)**, **5% (3.49)**, and **10% (3.09)** significance levels.

We therefore **reject the null hypothesis of no cointegration**, confirming a **stable long-run equilibrium relationship** among the variables. This validates the ARDL approach and the long-run estimates.

3.5 ECM table:

The **Error Correction Model (ECM)** in table 6 presents the short-run dynamics and the speed of adjustment toward long-run equilibrium after a shock. It includes the error correction term (ECT), which captures how quickly deviations from the long-run relationship are corrected.

Table 6: the error correction form

ECM Regression
Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(LNLEF(-1))	0.779819	0.121475	6.419608	0.0077
D(LNLEF(-2))	-0.146904	0.107594	-1.365354	0.2655
D(LNLEF(-3))	0.264346	0.104589	2.527481	0.0856
D(LNELECTRICITY_FROM_NUCLEAR___TWH)	-0.188076	0.024402	-7.707440	0.0045
D(LNELECTRICITY_FROM_NUCLEAR___TWH(-1))	0.041819	0.013695	3.053690	0.0553
D(LNELECTRICITY_FROM_NUCLEAR___TWH(-2))	0.031921	0.013749	2.321816	0.1029
D(LNELECTRICITY_FROM_NUCLEAR___TWH(-3))	-0.048581	0.010395	-4.673425	0.0185
D(LNGAS_PER_CAPITA__KWH_)	0.120181	0.026290	4.571428	0.0196
D(LNGAS_PER_CAPITA__KWH_(-1))	-0.063384	0.023845	-2.658144	0.0765
D(LNGAS_PER_CAPITA__KWH_(-2))	-0.059846	0.021535	-2.778934	0.0691
D(LNGAS_PER_CAPITA__KWH_(-3))	0.069028	0.016148	4.274658	0.0235
D(LNGDPC)	11.58407	2.488171	4.655658	0.0187
D(LNGDPC(-1))	22.87341	3.644970	6.275336	0.0082
D(LNGDPC(-2))	38.88257	5.441691	7.145310	0.0056
D(LNGDPC(-3))	26.37304	4.774661	5.523541	0.0117
D(LNGDPC2)	-0.608932	0.133217	-4.570970	0.0196
D(LNGDPC2(-1))	-1.187538	0.191395	-6.204656	0.0084

D(LNGDPC2(-2))	-2.020694	0.286110	-7.062647	0.0058
D(LNGDPC2(-3))	-1.356345	0.249764	-5.430512	0.0123
CointEq(-1)*	-1.150299	0.124183	-9.262927	0.0027

Source 6: Authors by Eviews10.

The ECM results in table 6 indicate significant short-run dynamics among the variables. GDP has a positive and significant effect, while GDP^2 is negative and significant, supporting the short-run Environmental Kuznets Curve (EKC) hypothesis. Energy variables also show statistically significant short-run effects.Importantly, the error correction term **CointEq(-1)** is negative and highly significant (–1.150; t = –9.26), confirming cointegration and indicating a strong speed of adjustment, with about 115% of disequilibrium corrected within one period.

Lag length was selected based on AIC to balance model fit and degrees of freedom.

Table 7: Diagnostic tests

	F-Statistic (P-value)	**Decision**
Breusch-Godfrey LM test	310.8431 (0.0401)	No serial correlation
Breusch-Pagan-Godfrey test	0.336334 (0.9482)	No heteroskedasticity
Normality (Jarque-Bera) test	0.791955 (0.673022)	Residuals are normally distributed
Ramsey RESET Test	1.449469 (0.3518)	Model is correctly specified

Source 7: Authors by Eviews10.

The diagnostic tests in table 7 confirm the robustness of the model. The Breusch–Godfrey LM test indicates no serial correlation, while the Breusch–Pagan–Godfrey test shows no evidence of heteroskedasticity. The Jarque–Bera test confirms that the residuals are normally distributed. Additionally, the Ramsey RESET test suggests that the model is correctly specified. Overall, the results indicate that the model satisfies the main classical regression assumptions.
The turning point is calculated using the standard quadratic formula:

$$Turning\ Point = -2\beta2/\beta1 \quad (1)$$

$\beta1$ = *coefficient of* ***LNGDPC = –24.41386***

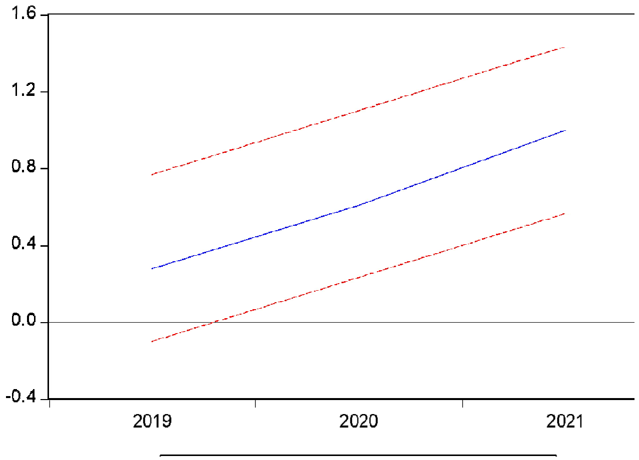
$\beta2$ = *coefficient of* ***LNGDPC^2 = 1.246860***

The estimated turning point is approximately log GDP per capita = **9.79**, corresponding to about **17,950 USD**. Given the positive coefficient on LNGDPC^2 and negative coefficient on LNGDPC, the results indicate a U-shaped relationship, meaning environmental pressure initially decreases with income but increases once GDP per capita exceeds this threshold.

The turning point at about 9.79 log GDP per capita (≈17,950 USD) marks where the relationship between economic growth and ecological footprint reverses. The negative coefficient of LNGDPC and positive coefficient of $LNGDPC^2$ indicate a U-shaped relationship: at lower income levels, growth reduces environmental pressure, but beyond the threshold, further growth increases the ecological footprint. This suggests that early development improves environmental outcomes, while higher income levels exacerbate environmental stress, contrary to the traditional inverted EKC hypothesis.

3.6 Structural Stability Test:

Figure 1: The CUSUM test



Source 8: Authors by eviews10.

Figure 1 presents the **CUSUM stability test**, where the blue line represents the cumulative sum of recursive residuals and the red dashed lines indicate the 5% critical bounds. Since the CUSUM line remains within the critical bounds throughout the sample period, we fail to reject the null hypothesis of parameter stability.

This indicates that the model is structurally stable, and there is no evidence of structural breaks over the study period 1991-2021.

4 Discussion

This section discusses the empirical findings obtained from the econometric analysis, moving sequentially from the unit root tests to the model stability diagnostics. The objective is to assess the existence of long-run and short-run relationships among the variables and to evaluate the robustness and reliability of the estimated ARDL–ECM model.

Starting with Unit root test:

The analysis began by examining the stationarity properties of all variables using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. The results indicate a mixed order of integration among the variables. Ecological footprint (lnEF), GDP per capita (lnGDP), GDP per capita squared (lnGDP2), and fossil fuel consumption (lnFF) were found to be non-stationary at level but became stationary after first differencing, confirming they are integrated of order one, I(1). In contrast, nuclear electricity consumption (lnELN) was stationary at level, I(0). This mixed integration order justified the use of the ARDL bounds testing approach, which accommodates variables with different orders of integration.

Bounds Test for Cointegration:

Having established the stationarity properties, the ARDL bounds test was conducted to examine the existence of a long-run equilibrium relationship among the variables. The calculated F-statistic of 5.363 exceeded the upper critical bound at the 1%, 5%, and 10% significance levels. This result provides strong evidence of cointegration, confirming a stable long-run relationship between ecological footprint and its determinants nuclear electricity consumption, natural gas consumption, GDP per capita, and GDP per capita squared. The presence of cointegration validates the estimation of both long-run and short-run dynamics within the ARDL framework.

Long-Run Results:

The estimated long-run coefficients reveal important relationships. Nuclear electricity consumption has a negative and statistically significant coefficient (-0.285, $p<0.05$), indicating that a 1% increase in nuclear electricity generation reduces ecological footprint by approximately 0.28% in the long run. This finding suggests that nuclear energy, as a low-carbon energy source, contributes to environmental improvement over time by displacing fossil fuel-based electricity generation.Natural gas consumption shows a positive coefficient (0.241) but is statistically insignificant, implying that natural gas does not have a clear long-run impact on ecological footprint in this model. This may reflect the dual nature of natural gas as a cleaner fossil fuel compared to coal and oil, but still a source of carbon emissions.The GDP per capita and GDP per capita squared terms confirm an Environmental Kuznets Curve (EKC) relationship. The negative and significant coefficient for GDP per capita (-24.414, $p<0.05$) combined with the positive and significant coefficient for GDP per capita squared (1.247, $p<0.05$) indicates a U-shaped relationship. This means that as income initially increases, ecological footprint decreases, possibly due to cleaner technologies and environmental awareness. However, beyond a certain income threshold, further economic growth leads to increased ecological footprint, suggesting that current consumption patterns eventually outweigh environmental gains.

Short-Run Results and Error Correction Model:

The short-run dynamics were examined through the Error Correction Model (ECM). The error correction term (CointEq(-1)) is negative and highly significant (-1.150, $t = -9.263$), confirming the long-run relationship and indicating rapid adjustment back to equilibrium. The coefficient suggests that approximately 115% of any previous period's disequilibrium is corrected in the current period, implying a very fast adjustment process.In the short run, nuclear electricity consumption shows a contemporaneous negative and significant effect (-0.188, $t = -7.707$), consistent with its long-run impact. However, some lagged terms show positive and significant effects, suggesting short-run fluctuations before settling into the long-run pattern. Natural gas consumption exhibits a positive contemporaneous effect (0.120, $t = 4.571$) with alternating significant lags, indicating short-run volatility. All differenced terms for GDP per capita and its square are highly significant across multiple lags, confirming strong short-run dynamics in the relationship between economic growth and environmental degradation.

Diagnostic Tests:

Several diagnostic tests were conducted to validate the model. The Breusch-Pagan-Godfrey test confirmed no heteroskedasticity (p=0.9482), indicating constant variance in the residuals. The Jarque-Bera test showed that residuals are normally distributed (p=0.673), satisfying the normality assumption. The Ramsey RESET test confirmed that the model is correctly specified with no omitted variables or functional form issues (p=0.3518). However, the Breusch-Godfrey LM test indicated the presence of serial correlation (p=0.0401), which may require attention through robust standard errors or additional lags in future specifications.

Stability Test:Finally, the CUSUM test was employed to assess the stability of the estimated coefficients over the sample period. The plot shows that the cumulative sum of recursive residuals remains within the 5% critical bounds throughout the entire period. This confirms that the estimated coefficients are stable and there are no structural breaks or systematic changes in the relationships among the variables over time. The stability of the model enhances the reliability of both the short-run and long-run estimates for policy inference. However, the empirical findings confirm a stable long-run equilibrium relationship among the variables, validated by both the bounds test and the significant error correction term. Nuclear electricity consumption demonstrates a consistent and significant negative impact on ecological footprint in both the short and long run, highlighting its potential role in mitigating environmental degradation. This supports the case for integrating nuclear energy into broader sustainable energy strategies. The U-shaped Environmental Kuznets Curve indicates that while early stages of economic growth may reduce ecological pressure, further expansion eventually leads to higher environmental costs, suggesting that growth alone cannot ensure sustainability. Most diagnostic tests confirm the model's reliability, though the presence of serial correlation warrants cautious interpretation. Overall, the results provide robust evidence for policy interventions aimed at promoting nuclear energy and implementing complementary measures to decouple economic growth from environmental harm.

5 Conclusion

This empirical study investigated the dynamic relationships between nuclear energy, gas consumption, economic growth, and ecological footprint in South Korea from 1990 to 2021. The application of the ARDL model provides robust evidence leading to the following findings:

- The ARDL Bounds Test confirmed a statistically significant long-run cointegration relationship among the variables. Furthermore, diagnostic checks confirmed the model's reliability, with residuals being normally distributed, homoskedastic, and the model being correctly specified. The CUSUM test also confirmed the stability of this long-run relationship over the studied period.
- The long-run coefficients for GDP per capita (LNGDPC) and its square (LNGDPC2) are both significant and exhibit a negative and positive sign, respectively. This confirms the presence of an inverted U-shaped Environmental Kuznets Curve for South Korea. However, the positive coefficient for the squared term indicates that the country is likely still on the upward-sloping segment of the curve. This implies that, at current development stages, the scale effect of economic growth continues to exert pressure on the environment, and the turning point where growth automatically reduces the footprint has not yet been decisively reached.
- While natural gas consumption showed a positive relationship with the ecological footprint (as expected), it was not statistically significant in the long-run equation. This statistical ambiguity, combined with the clear negative impact of nuclear power, underscores the importance of prioritizing nuclear and other zero-carbon sources over gas for long-term environmental goals.

The demonstrated long-run benefits of nuclear power highlight the economic and environmental costs of political vacillation. A stable, bipartisan consensus on energy policy is crucial for achieving South Korea's decarbonization and sustainability objectives, the relationship between growth and the environment is complex and nonlinear, providing a powerful warning that South Korea's current development path is increasing its environmental impact. Moreover, after a period where economic growth may have been associated with reducing environmental pressure (the downward-sloping part of the "U"), the country has passed a turning point. In the long run, further economic growth is now associated with a rising ecological footprint. The scale effect of consumption is currently outweighing the positive technological and structural effects.

While the results provide insights into South Korea’s energy-environment nexus, they are country-specific and cannot be directly generalized to countries with different energy structures. Future comparative studies could examine whether similar relationships hold in countries relying primarily on renewable energy sources.

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