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Asymmetric Effects of the Sustainable Energy Policy Index and Socioeconomic Development on the Ecological Footprint with Emphasis on Institutional Quality in Iran

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Abstract

At present, economic development on the one hand and the preservation of the Earth's environment on the other have become major challenges for humanity. Global warming, air pollution, marine pollution, soil erosion, desertification, and other environmental crises are the outcomes of human economic activities along the development path. If environmental quality, as the foundation of development, is neglected, not only will the development trajectory for future generations be halted, but it may also reverse, implicitly signaling future unsustainability. Since any effort to enhance human quality of life is realized within the environment, the condition of environmental resources significantly influences the sustainability or unsustainability of the development process. Accordingly, any discussion of sustainable development without considering environmental sustainability is incomplete. The ecological footprint reflects the extent of human use of natural resources and serves as an indicator of environmental sustainability. In this study, the role of institutional quality as a moderating factor in the relationship between energy policies, economic development, and environmental conditions is examined. The objective is to achieve a precise understanding of how economic and institutional variables influence environmental sustainability in Iran. This study investigates the asymmetric effects of the sustainable energy policy index and socioeconomic development on the ecological footprint, emphasizing the role of institutional quality in Iran over the period 1991–2024. To this end, the NARDL model is employed to assess the differential impacts of positive and negative changes in variables on environmental sustainability in both the short and long run. The estimation results indicate that, in the long run, improvements in institutional quality significantly reduce the ecological footprint; effective governance, corruption control, and enhanced institutional accountability play a moderating role in the relationship between economic development and environmental degradation. Furthermore, sustainable energy policies, through improving energy efficiency and expanding renewable energy sources, exert a significant negative effect on the ecological footprint, whereas reductions in these policies have a stronger asymmetric effect in increasing it. On the other hand, economic development and urbanization, if pursued without environmental considerations, lead to an increase in the ecological footprint; however, in the presence of high-quality institutions and sustainable energy policies, their adverse effects can be mitigated. Short-run results also indicate that positive shocks to institutional quality and renewable energy reduce the ecological footprint, whereas negative shocks in economic development and natural resource consumption exert destructive effects on the environment. Overall, the findings suggest that achieving sustainable development in Iran requires strengthening institutional quality, implementing sustainable energy policies, and directing economic development toward green growth.

Keywords: *Sustainable Energy Policy, Institutional Quality, Socioeconomic Development, Ecological Footprint, Good Governance*

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1. Introduction

The accelerating pace of economic growth over recent decades has intensified the pressure exerted on natural ecosystems, transforming environmental sustainability into a central concern in both academic and policy discourses. While economic expansion has contributed to improvements in living standards, industrial productivity, and technological advancement, it has simultaneously resulted in increased resource extraction, environmental degradation, and ecological imbalance. The tension between economic development and environmental preservation has thus emerged as one of the defining challenges of contemporary development paradigms. In this context, the concept of sustainable development has gained prominence, emphasizing the necessity of balancing economic, social, and environmental objectives to ensure intergenerational equity. The ecological footprint, as a comprehensive indicator of environmental pressure, provides a valuable framework for assessing the extent to which human activities exceed the regenerative capacity of natural ecosystems, thereby offering critical insights into the sustainability of development processes [1, 2].

The ecological footprint has been widely adopted in empirical research as a multidimensional measure that captures the environmental consequences of production and consumption patterns. Unlike traditional environmental indicators that focus on single dimensions such as carbon emissions, the ecological footprint integrates various environmental impacts, including land use, energy consumption, and waste generation, into a unified metric. This integrative approach enables researchers to evaluate environmental sustainability more holistically and to identify the key drivers of ecological degradation. Recent studies have demonstrated that factors such as energy consumption patterns, urbanization, industrialization, and economic growth significantly influence ecological footprints across different regions and development stages [3-5].

Among the determinants of environmental sustainability, energy consumption has received particular attention due to its direct and indirect effects on ecological systems. The reliance on fossil fuels as the primary source of energy has been identified as a major contributor to greenhouse gas emissions and environmental degradation. Consequently, the transition toward sustainable energy systems, characterized by increased use of renewable energy sources and improved energy efficiency, has become a key policy priority in many countries. Empirical evidence suggests that renewable energy consumption can significantly reduce ecological footprints by mitigating carbon emissions and promoting cleaner production processes. However, the effectiveness of sustainable energy policies depends on the extent to which they are integrated into broader economic and institutional frameworks [6-9].

In addition to energy-related factors, socioeconomic development plays a critical role in shaping environmental outcomes. Economic growth, while essential for improving welfare, often leads to increased resource consumption and environmental pressure, particularly in the early stages of development. This phenomenon is frequently explained through the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between income levels and environmental degradation. However, the empirical validity of this hypothesis remains contested, as the environmental impact of economic growth varies across countries depending on structural characteristics, policy frameworks, and institutional quality. In developing economies, rapid urbanization and industrialization often exacerbate environmental challenges, while in more advanced economies, technological innovation and regulatory measures may help decouple economic growth from environmental degradation [10-12].

Urbanization, in particular, has been identified as a significant driver of ecological pressure due to its association with increased energy demand, infrastructure development, and consumption patterns. The expansion of urban areas often leads to higher levels of pollution, waste generation, and resource depletion, thereby contributing to the growth of ecological footprints. Nevertheless, urbanization also presents opportunities for improving environmental efficiency through the development of sustainable infrastructure, public transportation systems, and smart urban planning. Studies have shown that investments in public transportation and urban sustainability initiatives can mitigate the environmental impact of urbanization by reducing reliance on private vehicles and promoting energy-efficient mobility systems [13, 14].

Another critical determinant of environmental sustainability is the role of natural resources and their management. Resource-rich countries often face the paradox of resource abundance, where excessive reliance on natural resources leads to environmental degradation and economic vulnerability. The extraction and consumption of fossil fuels and other natural resources contribute significantly to ecological footprints, particularly when environmental regulations are weak or poorly enforced. Empirical research has highlighted the importance of sustainable resource management and human capital development in mitigating the environmental impact of natural resource utilization [15, 16].

Institutional quality has emerged as a key moderating factor in the relationship between economic activities and environmental outcomes. Strong institutions, characterized by effective governance, transparency, accountability, and rule of law, play a crucial role in implementing environmental regulations, promoting sustainable practices, and ensuring efficient resource allocation. Conversely, weak institutional frameworks can exacerbate environmental degradation by enabling corruption, regulatory inefficiencies, and unsustainable exploitation of natural resources. Empirical evidence indicates that improvements in institutional quality can significantly reduce ecological footprints by enhancing policy effectiveness and fostering sustainable development practices [17, 18].

Furthermore, the role of foreign direct investment (FDI) in environmental sustainability has been widely debated in the literature. While FDI can contribute to economic growth and technological transfer, its environmental impact depends on the nature of investments and the regulatory environment of the host country. In some cases, FDI may lead to increased environmental degradation through the relocation of pollution-intensive industries, a phenomenon known as the "pollution haven" hypothesis. In other cases, it may promote environmental sustainability by introducing cleaner technologies and more efficient production processes. The net effect of FDI on ecological footprints is therefore contingent upon the interaction between economic, institutional, and environmental factors [11, 19].

Recent advances in the literature have also emphasized the importance of considering nonlinear and asymmetric relationships between economic variables and environmental outcomes. Traditional linear models may fail to capture the complex dynamics of environmental systems, where positive and negative changes in explanatory variables can have متفاوت impacts on ecological indicators. The application of nonlinear econometric approaches, such as the NARDL model, allows researchers to differentiate between the effects of positive and negative shocks and to provide a more nuanced understanding of the underlying relationships. Studies employing such approaches have demonstrated that the impact of variables such as energy consumption, economic growth, and institutional quality on ecological footprints is often asymmetric, highlighting the need for more sophisticated analytical frameworks [20, 21].

In the context of Iran, environmental sustainability has become an increasingly pressing issue due to rapid economic growth, population expansion, and reliance on fossil fuel-based energy systems. The country faces significant environmental challenges, including air pollution, water scarcity, and land degradation, which have contributed to the افزایش ecological footprint. Despite the implementation of various policy measures aimed at promoting renewable energy and environmental protection, the effectiveness of these initiatives remains limited due to structural and institutional constraints. Understanding the interplay between sustainable energy policies, socioeconomic development, and institutional quality is therefore essential for designing effective strategies to achieve sustainable development in Iran [16, 18].

Given the complexity of these relationships, there is a growing need for empirical studies that integrate economic, energy, and institutional dimensions within a unified analytical framework. While previous research has examined the individual effects of these factors on environmental outcomes, relatively few studies have explored their combined and asymmetric impacts, particularly in the context of developing economies such as Iran. Moreover, the role of institutional quality as a moderating variable in these relationships has not been sufficiently addressed in the existing literature, despite its critical importance in shaping policy effectiveness and environmental performance [8, 9, 22].

Therefore, this study aims to investigate the asymmetric effects of the sustainable energy policy index and socioeconomic development on the ecological footprint, with emphasis on the moderating role of institutional quality in Iran.

2. Methodology

This study examines the asymmetric effects of the sustainable energy policy index and socioeconomic development on the ecological footprint, with emphasis on institutional quality in Iran. In terms of objective, the research is applied, and in terms of nature, it is descriptive-analytical. It falls within the category of ex post facto studies, utilizing statistical data over the period 1991–2024. The empirical model is implemented using the Nonlinear Autoregressive Distributed Lag (NARDL) approach for Iran. Based on the theoretical framework and considering empirical studies by Ji et al. (2023), Sarwar et al. (2024), and Georgescu et al. (2024), the regression model is specified as follows:

$$COE = f(URB, FDI, SD, L, NRS, RENE, GOV, CAP)$$

The estimable model is expressed as follows:

By rewriting Equation (2) in an error correction form and decomposing the variables institutional quality ($\ln GOV$)and sustainable development ($\ln SD$)into partial sums of positive and negative changes—namely, positive changes in institutional quality

$$POSE = \sum_{j=1}^{t} \Delta\ln\ GOV^{+}$$

positive changes in sustainable development

$$POSS = \sum_{j=1}^{t} \Delta\ln\ SD^{+}$$

negative changes in institutional quality

$$NEGE = \sum_{j=1}^{t} \Delta\ln\ GOV^{-}$$

and negative changes in sustainable development

$$NEGS = \sum_{j=1}^{t} \Delta\ln\ SD^{-}$$

—it becomes possible to estimate the nonlinear (asymmetric) short-run and long-run effects of sustainable energy policy, socioeconomic development, and ecological footprint as follows:

$$\begin{aligned}\ln COE_t = \mu \quad & + \sum_{i=1}^{n_1} \beta_i \Delta\ln\ URB_{t-i} + \sum_{i=1}^{n_2} \beta_i \Delta\ln\ FDI_{t-i} + \sum_{i=1}^{n_3} \beta_i \Delta\ln\ NRS_{t-i} \\ & + \sum_{i=1}^{n_4} \beta_i \Delta\ln\ NRENE_{t-i} + \sum_{i=1}^{n_4} \beta_i \Delta\ln\ CAP_{t-i} + \sum_{i=1}^{n_4} \beta_i \Delta\ln\ L_{t-i} \\ & + \sum_{i=1}^{n_5} \beta_{1,i} \Delta\ln\ POSE_{t-i} + \sum_{i=1}^{n_6} \beta_{2,i} \Delta\ln\ NEGE_{t-i} \\ & + \sum_{i=1}^{n_7} \beta_{3,i} \Delta\ln\ POSS_{t-i} + \sum_{i=1}^{n_8} \beta_{4,i} \Delta\ln\ NEGS_{t-i} + \varepsilon_t\end{aligned}$$

In this model, the variables are defined as follows:

Model Variables:

(COE): Ecological Footprint

According to Georgescu et al. (2024) and Sarwar et al. (2024), the ecological footprint is calculated based on three greenhouse gases: CO_2, CH_4, and N_2O. Their emissions are derived from the product of energy consumption and emission coefficients of 1, 21, and 310, respectively, per joule of energy consumed from each source. Considering the different global warming potentials of CH_4 and N_2O, total emissions are expressed in CO_2-equivalent terms. Specifically, each kilogram of N_2O and CH_4 is equivalent to 310 and 21 kilograms of CO_2, respectively. After calculating the total Global Warming Potential (GWP), the values are expressed per unit area (kg CO_2 per hectare), per unit weight (kg CO_2 per ton), per unit of input energy (kg CO_2 per gigajoule), and per unit of output energy (kg CO_2 per gigajoule).

After computing Equation (2), it is incorporated into the model as the ecological footprint index.

NRSOURCES: Natural resource abundance is calculated, following the literature, as:

$$RA_t = \frac{\alpha_1 \cdot Coal + \alpha_2 \cdot Oil + \alpha_3 \cdot Gas}{Population}$$

RENRGY: Sustainable energy policy index This index is measured as the share of clean (renewable) energy consumption in total energy consumption, based on World Bank data.

Institutional Quality (GOV):

This variable represents the average institutional quality index, composed of five dimensions: (1) size of government, (2) legal system and property rights, (3) accountability and transparency, (4) international trade freedom, and (5) regulation of credit, labor, and business. Each dimension includes subcomponents that contribute to the overall index. The Fraser Institute assigns scores to each category and computes their average to obtain a composite index for each country. The index ranges from 0 (lowest institutional quality) to 5 (highest institutional quality).

URB: Urban population growth rate (World Bank).

CAP: Gross fixed capital formation per capita in USD (growth rate percentage).

SD_t: Socioeconomic Development Index

This index is based on the sustainable development index provided by the World Bank, which offers comprehensive and up-to-date information on global development. It measures country performance across multiple dimensions, including poverty, health, hunger, climate change, gender inequality, water scarcity, energy, and environmental degradation. The index ranges from 0 to 1, where higher values indicate higher levels of sustainable development and lower values indicate lower levels (World Bank, 2020).

L: Labor force participation rate as a percentage of the total population.

3. Findings and Results

Initially, to ensure the absence of spurious regression, unit root and cointegration tests are conducted. In this study, the Phillips–Perron (PP) test is employed.

Table 1. Results of the Phillips–Perron (PP) Unit Root Test for Model Variables

Variable	Test Statistic	Probability	Integration Order
CAP	2.225271	0.9999	---
D(CAP)	-6.760581	0.0000	I(1)
COE	-2.548618	0.1163	---
D(COE)	-5.067880	0.0004	I(1)
FDI	-1.653764	0.4419	---
D(FDI)	-4.308678	0.0025	I(1)
GOV	1.343054	0.9981	---
D(GOV)	-4.332708	0.0024	I(1)
L	-1.909070	0.3232	---
D(L)	-4.917010	0.0006	I(1)
NRS	-1.342299	0.5942	---
D(NRS)	-6.364033	0.0000	I(1)
RENE	-2.113231	0.2413	---
D(RENE)	-5.929768	0.0001	I(1)
SD	-7.494417	0.0000	I(0)
URB	-5.789769	0.0001	I(0)

Given the non-stationarity of several variables and the mixed order of integration, conventional cointegration tests such as the Johansen test are not applicable. Therefore, the NARDL model is employed to estimate the regression.

In the NARDL framework, it is not necessary for all variables to be integrated of the same order. One of the key advantages of this method is that it provides consistent estimates of long-run coefficients regardless of whether variables are integrated of order $I(0)$, $I(1)$, or even $I(2)$.

Initially, to detect the existence of a long-run equilibrium relationship among the model variables, cointegration testing is employed. For this purpose, the Johansen–Juselius method is used. To implement this test, the number of cointegrating vectors must be determined. In examining the results of the cointegration test, it is necessary to select an appropriate model regarding the presence or absence of a deterministic trend and intercept in the cointegration vector. In this regard, five alternative models are considered: Model 1 (no intercept and no trend), Model 2 (restricted intercept and no trend), Model 3 (unrestricted intercept and no trend), Model 4 (unrestricted intercept with restricted trend), and Model 5 (unrestricted intercept and unrestricted trend). These models range from the most restricted (Model 1) to the least restricted (Model 5). Subsequently, the null hypothesis of no cointegrating vector is tested against the alternative of at least one cointegrating vector, followed by testing the hypothesis of at most one cointegrating vector against two cointegrating vectors. This procedure continues up to $n-1$cointegrating vectors (where $n$is the number of variables). A summary of the results of the Trace statistic (λ_{Trace})and Maximum Eigenvalue statistic (λ_{Max})for determining the number of cointegrating vectors under the five models is presented in Table 2. As observed, the null hypothesis of no cointegrating vector is rejected in favor of the existence of at least one cointegrating vector among the variables.

Table 2. Summary of the Number of Cointegrating Vectors

Model	Model 1	Model 2	Model 3	Model 4	Model 5
Trace Test	4	4	9	5	7
Max-Eigen Test	6	3	5	8	2

The estimation results and cointegration tests based on Model 3 of the Johansen test are reported in the following table. According to the Trace test results, there are 9 cointegrating vectors, and based on the Maximum Eigenvalue test, 5 cointegrating vectors are confirmed at the 5% significance level.

Table 3. Results of the Johansen Cointegration Test

Max-Eigen Statistic	95% Critical Value	Probability	Trace Statistic	95% Critical Value	Probability	H_1	H_0
101.5471	58.43354	0.0000	348.5925	197.3709	0.0000	$r = 1$	$r = 0$
58.01775	52.36261	0.0119	247.0454	159.5297	0.0000	$r = 2$	$r \leq 1$
51.93304	46.23142	0.0111	189.0276	125.6154	0.0000	$r = 3$	$r \leq 2$
42.46551	40.07757	0.0264	137.0946	95.75366	0.0000	$r = 4$	$r \leq 3$
37.25294	33.87687	0.0190	94.62909	69.81889	0.0002	$r = 5$	$r \leq 4$
20.76930	27.58434	0.2904	57.37616	47.85613	0.0050	$r = 6$	$r \leq 5$
15.61305	21.13162	0.2483	36.60685	29.79707	0.0070	$r = 7$	$r \leq 6$
14.20228	14.26460	0.0511	20.99380	15.49471	0.0067	$r = 8$	$r \leq 7$
6.791517	3.841466	0.0092	6.791517	3.841466	0.0092	$r = 9$	$r \leq 8$

Engle and Granger (1987) stated that if the Dickey–Fuller test is applied to the residuals of a model and the residual series is stationary, this confirms cointegration.

Table 4. Engle–Granger Cointegration Test

Test Statistic	Probability
-4.008914	0.0050

However, caution must be exercised when using this method, as the critical values are not entirely appropriate, and the specific critical values provided by Engle and Granger should be used. In this case, stationarity and non-stationarity are examined using the Dickey–Fuller unit root test.

Table 5. Estimation Results of the Ecological Footprint Model

Variable	Coefficient	Std. Error	t-Statistic	Probability
COE(-1)	0.196692	0.095788	2.053411	0.0549
DLnURB	0.513400	0.157400	3.262762	0.0098
DLnFDI	0.593920	0.289288	2.053044	0.0703
DLnSD_POS	-0.474573	0.124633	-3.807772	0.0066
DLnSD_NEGE	0.112346	0.033569	3.346760	0.0036
DLnL	0.228524	0.054462	4.196024	0.0005
DLnNRS	0.242560	0.040182	6.036585	0.0002
DLnRENE_POS	-0.203325	0.054194	-3.751771	0.0045
DLnRENE_NEGE	0.116226	0.039950	2.909323	0.0094
DLnGOV_POS	-0.850933	0.336984	-2.525142	0.0212
DLnGOV_NEGE	0.137959	0.041832	3.297954	0.0040
DLnCAP	0.521203	0.272529	1.912466	0.0974
ECM(-1)	-0.723252	0.050810	-14.23457	0.0000
Diagnostic Tests				
LM Test	Heteroskedasticity Test	Wald Test	Normality Test	LM Test
0.45263 (0.6123)	0.2684 (0.9586)	45.15060 (0.0000)	87.9865 (0.0000)	0.45263 (0.6123)

To examine the statistical significance of the coefficients of independent variables, the t-statistic is employed.

The results of the Wald test presented at the bottom of the table indicate that, in the short run, the null hypothesis of equality of coefficients for positive and negative shocks of the socioeconomic development index, sustainable energy policy index, and institutional quality is rejected, and the alternative hypothesis is accepted. Therefore, the asymmetric effects of positive and negative shocks of these variables on the ecological footprint are confirmed.

The findings indicate that negative fluctuations in the socioeconomic development index have a positive effect, while positive fluctuations have a negative effect on the ecological footprint in the short run. Thus, in this model, the socioeconomic development index has an inverse relationship with the ecological footprint. By separating positive and negative shocks, the coefficients reveal that the ecological footprint responds differently to each type of fluctuation, confirming the presence of asymmetric effects. The t-test results further validate this asymmetry by rejecting the null hypothesis of equal coefficients.

The findings also show that negative fluctuations in institutional quality have a positive effect, whereas positive fluctuations have a negative effect on the ecological footprint in the short run. Hence, institutional quality exhibits an inverse relationship with the ecological footprint. The decomposition of shocks demonstrates that the ecological footprint responds differently to positive and negative changes, confirming asymmetric effects, which are further supported by the rejection of the null hypothesis in the t-test.

Similarly, the results indicate that negative fluctuations in the sustainable energy policy index have a positive effect, while positive fluctuations have a negative effect on the ecological footprint in the short run. Therefore, the sustainable energy policy index also has an inverse relationship with the ecological footprint. The decomposition into positive and negative shocks confirms that the responses are asymmetric, and this is statistically supported by the rejection of the null hypothesis in the t-test.

The short-run coefficients extracted from the asymmetric error correction model show that the variables of urbanization, foreign direct investment, labor force, natural resource abundance, and capital have positive coefficients equal to 0.513400, 0.593920, 0.228524, 0.242560, and 0.521203, respectively. Based on the reported probabilities, these variables are statistically significant at the 95% confidence level (except for capital, which is significant at the 10% level).

Finally, the error correction term $ECM = -0.723252$indicates two important points. First, due to its negative sign, the convergence from short-run disequilibrium to long-run equilibrium is confirmed. Second, the magnitude of the ECM coefficient reflects the speed at which short-run deviations adjust toward long-run equilibrium.

To ensure the validity and reliability of the estimated model results, diagnostic tests for serial autocorrelation and heteroskedasticity were performed on the residuals of the NARDL model.

Table 6. Results of the Model Diagnostic Tests

Diagnostic Test	Result
LM Serial Correlation Test	Prob = 0.6123
Breusch–Pagan–Godfrey Heteroskedasticity Test	Prob = 0.9586
Ramsey RESET Specification Error Test	Prob = 0.3690

As the diagnostic test results reported in the above table indicate, the estimated model does not suffer from heteroskedasticity, specification error, or serial autocorrelation. This confirms the robustness and validity of the estimated model results.

In addition, to calculate the long-run test statistic of the model, the Banerjee and Dolado approach is applied using the same dynamic model. The long-run coefficients associated with the Xvariables are obtained from the following relationship:

$$\text{Long-run coefficients} = \frac{\text{estimated short-run coefficients}}{1 - \sum \text{coefficients of lagged dependent variable}}$$

To verify that the long-run relationship obtained from this method is not spurious, the following hypothesis is tested:

H_0: No cointegration or no long-run relationship exists

H_1: Cointegration or a long-run relationship exists

The null hypothesis indicates the absence of cointegration or a long-run relationship. The condition for the short-run dynamic relationship to converge toward long-run equilibrium is that the sum of the coefficients must be less than one. The alternative hypothesis, by contrast, indicates the existence of cointegration or a long-run relationship.

To perform this test, the value of one is subtracted from the sum of the coefficients of the lagged dependent variable, and the result is divided by the sum of the standard errors of those coefficients.

If the absolute value of the calculated t-statistic exceeds the absolute value of the critical values reported by Banerjee, Dolado, and Mestre, the null hypothesis is rejected and cointegration, or the existence of a long-run relationship, is accepted.

The calculated statistic is equal to -8.38. Since the absolute value of this number is greater than the critical value reported in the Banerjee, Dolado, and Mestre table (-3.27), the null hypothesis of no long-run relationship is rejected. Therefore, the model variables are cointegrated.

The calculated statistic is obtained as follows:

$$\frac{(0.196692-1)}{0.095788} = -8.386311$$

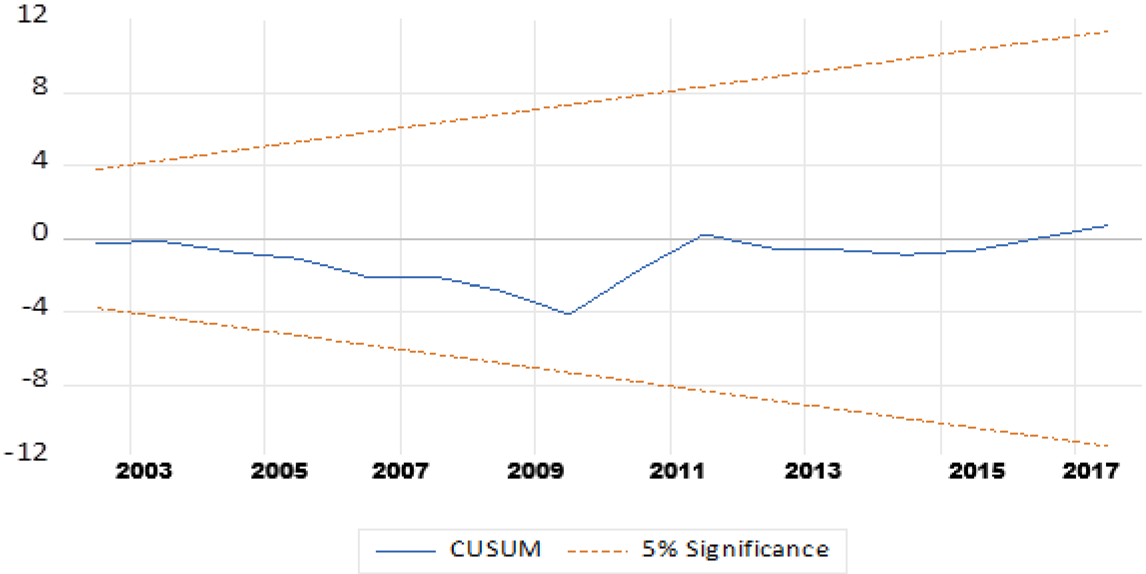
The results of the long-run NARDL estimation are presented in Table 7.

Table 7. Long-Run NARDL Estimation

Variable	Coefficient	Std. Error	t-Statistic	Probability
LN(URB)	0.123066	0.026111	4.713159	0.0002
LN(FDI)	-0.237409	0.102221	-2.322508	0.0321
LN(SD)	-0.225637	0.062077	-3.634768	0.0019
LN(L)	0.251691	0.097504	2.581332	0.0188
LN(NRS)	0.063825	0.023099	2.763094	0.0145
LN(RENE)	-0.070174	0.026734	-2.624946	0.0191
LN(GOV)	-0.437643	0.207664	-2.107460	0.0494
LN(CAP)	0.379810	0.141282	2.688308	0.0150
C	0.376683	0.176713	2.131606	0.0471

The obtained results indicate that all model variables are statistically significant in the long run at the 5% error level.

To test structural stability, the cumulative sum of recursive residuals (CUSUM) and the cumulative sum of squares of recursive residuals (CUSUMSQ), proposed by Brown, are employed.



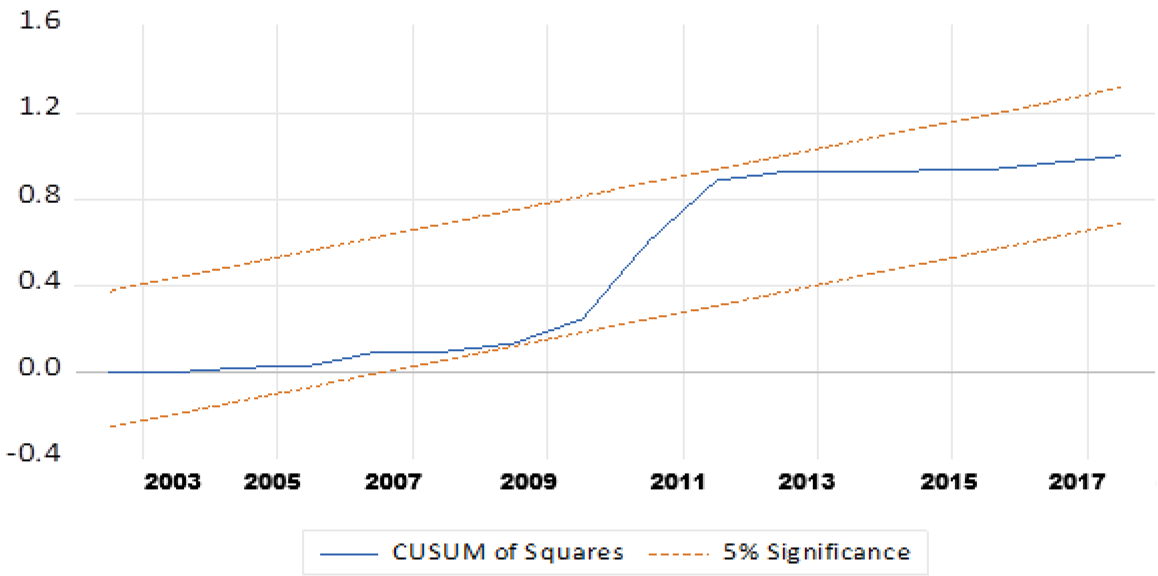


Figure 1. CUSUM and CUSUMSQ Tests

As can be observed, the plots of the cumulative residuals and the cumulative sum of squared residuals lie between the two straight lines representing the 95% confidence interval.

If the plotted curve remains within the confidence interval, the null hypothesis of no structural break is accepted. If the curve moves outside the confidence interval, that is, crosses the confidence bounds, the null hypothesis of no structural break is rejected and the existence of a structural break is accepted. Furthermore, the CUSUM statistic is used to detect systematic changes in the regression coefficients, whereas the CUSUMSQ statistic is applied when deviations from coefficient stability are sudden and random.

4. Discussion and Conclusion

The results of the present study provide robust empirical evidence regarding the asymmetric effects of the sustainable energy policy index, socioeconomic development, and institutional quality on the ecological footprint in Iran. The estimated NARDL model reveals that both in the short run and the long run, the relationships between the explanatory variables and the ecological footprint are nonlinear and asymmetric, indicating that positive and negative shocks do not exert identical effects. In the short run, positive shocks to the sustainable energy policy index significantly reduce the ecological footprint, while negative shocks increase it, confirming the presence of asymmetry. This finding highlights the sensitivity of environmental outcomes to policy reversals or inefficiencies in energy transitions. Similarly, positive changes in institutional quality reduce ecological pressure, whereas deterioration in governance increases it, reflecting the critical role of institutional effectiveness in environmental management. Moreover, socioeconomic development exhibits an inverse relationship with the ecological footprint in the short run, where improvements in development reduce environmental pressure, while declines intensify ecological degradation.

In the long run, the results indicate that institutional quality plays a decisive role in reducing the ecological footprint. The negative and statistically significant coefficient of institutional quality suggests that improvements in governance, accountability, and regulatory efficiency contribute to environmental sustainability. This finding is consistent with prior studies emphasizing that strong institutions enhance the effectiveness of environmental policies and mitigate ecological degradation [17, 18]. Effective institutional frameworks facilitate the enforcement of environmental regulations, reduce corruption, and promote the adoption of sustainable technologies, thereby lowering ecological footprints. Conversely, weak institutional structures can exacerbate environmental problems by allowing inefficient resource allocation and regulatory failures.

The results also demonstrate that sustainable energy policy has a significant negative impact on the ecological footprint in the long run. This implies that increased reliance on renewable energy sources and improved energy efficiency can substantially reduce environmental pressure. These findings align with the empirical literature suggesting that renewable energy consumption contributes to environmental sustainability by lowering greenhouse gas emissions and reducing dependence on fossil fuels [6-9]. Furthermore, the asymmetric nature of the relationship indicates that reductions in renewable energy policies have a stronger adverse effect compared to the beneficial effects of their expansion, emphasizing the importance of policy consistency and long-term commitment to clean energy transitions.

Socioeconomic development exhibits a negative relationship with the ecological footprint in the long run, suggesting that higher levels of development are associated with improved environmental outcomes. This finding provides partial support for the Environmental Kuznets Curve hypothesis, indicating that as economies progress, they may adopt cleaner technologies and more efficient production processes that reduce environmental degradation. This result is consistent with previous studies showing that economic development, when accompanied by structural transformation and technological advancement, can lead to environmental improvements [10, 12]. However, the asymmetric effects observed in this study suggest that negative shocks to socioeconomic development can have disproportionately harmful environmental consequences, highlighting the vulnerability of environmental systems to economic instability.

Urbanization, foreign direct investment, labor force participation, natural resource abundance, and capital formation all exhibit positive and significant effects on the ecological footprint in the short run. These findings indicate that increases in these variables are associated with higher environmental pressure, reflecting the resource-intensive nature of economic activities in developing economies. The positive impact of urbanization on the ecological footprint is consistent with previous research indicating that rapid urban expansion leads to increased energy consumption, pollution, and waste generation [13, 14]. Similarly, the positive relationship between foreign direct investment and ecological footprint supports the “pollution haven” hypothesis, suggesting that foreign investments may concentrate in environmentally sensitive sectors in countries with weaker environmental regulations [11, 19].

Natural resource abundance is found to increase the ecological footprint, highlighting the environmental costs associated with resource extraction and consumption. This finding is in line with the resource curse hypothesis, which suggests that countries rich in natural resources may experience environmental degradation due to overexploitation and insufficient regulatory oversight [15, 16]. Additionally, the positive effect of labor force participation and capital formation reflects the expansion of economic activities that intensify environmental pressure, particularly in the absence of sustainable production practices.

The asymmetric decomposition of key variables provides further insights into the dynamics of environmental sustainability. The results show that negative shocks in institutional quality, sustainable energy policy, and socioeconomic development have stronger and more immediate effects on increasing the ecological footprint compared to the mitigating effects of positive shocks. This asymmetry underscores the importance of preventing policy deterioration and institutional decline, as their adverse environmental impacts may be more severe and difficult to reverse. The findings are consistent with recent studies emphasizing the nonlinear nature of environmental-economic relationships and the need for advanced econometric approaches to capture these dynamics [20, 21].

Furthermore, the significance of the error correction term confirms the existence of a stable long-run equilibrium relationship among the variables. The relatively high speed of adjustment indicates that deviations from long-run equilibrium are corrected efficiently over time, reflecting the dynamic interaction between economic, institutional, and environmental factors. This finding supports the validity of the NARDL framework in capturing both short-run dynamics and long-run relationships in environmental studies.

Overall, the results of this study highlight the interconnected roles of sustainable energy policies, socioeconomic development, and institutional quality in shaping environmental outcomes. The findings suggest that achieving environmental sustainability requires a comprehensive approach that integrates energy transition, economic development strategies, and institutional reforms. Policymakers should prioritize the development of renewable energy infrastructure, strengthen governance frameworks, and promote sustainable economic practices to reduce ecological footprints. The asymmetric nature of the relationships further emphasizes the need for consistent and stable policy implementation to avoid adverse environmental consequences.

One of the key contributions of this study is the incorporation of institutional quality as a moderating factor in the relationship between economic variables and environmental sustainability. By demonstrating that institutional quality significantly influences the effectiveness of energy policies and economic development, this study provides valuable insights for policymakers seeking to design integrated strategies for sustainable development. The findings also underscore the importance of adopting nonlinear analytical frameworks to better understand the complex dynamics of environmental systems.

In conclusion, the empirical evidence presented in this study confirms that sustainable energy policies, socioeconomic development, and institutional quality play crucial roles in determining the ecological footprint in Iran. The asymmetric effects identified in this research highlight the need for targeted policy interventions that account for the differential impacts of positive and negative changes in key variables. By aligning economic growth with environmental sustainability and strengthening institutional frameworks, it is possible to achieve a more balanced and sustainable development trajectory.

One limitation of this study is the reliance on aggregated national-level data, which may mask regional heterogeneity in environmental and economic dynamics. Additionally, the measurement of institutional quality and sustainable energy policies is based on composite indices, which may not fully capture the complexity of these constructs. The use of the NARDL model, while effective in identifying asymmetric relationships, also imposes certain methodological constraints, particularly regarding lag selection and model specification. Furthermore, the study does not explicitly account for potential external shocks such as geopolitical developments or global energy market fluctuations, which may influence environmental outcomes.

Future research can extend the present study by incorporating regional or provincial-level data to capture spatial variations in environmental sustainability. Moreover, the integration of additional variables such as technological innovation, environmental awareness, and policy enforcement mechanisms could provide a more comprehensive understanding of the determinants of ecological footprint. Employing alternative econometric approaches, such as panel data models or machine learning techniques, may also enhance the robustness of empirical findings. Longitudinal studies that examine the impact of policy changes over time would further contribute to the literature on sustainable development.

From a practical perspective, policymakers should focus on strengthening institutional frameworks to enhance the effectiveness of environmental policies. Promoting renewable energy adoption, improving energy efficiency, and investing in sustainable infrastructure are essential steps toward reducing ecological footprints. Additionally, implementing stricter environmental regulations and encouraging private sector participation in green technologies can facilitate the transition toward a low-carbon economy. Public awareness campaigns and education programs can also play a significant role in promoting sustainable consumption patterns and environmental responsibility.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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