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An Analysis on the Connection between Sustainable Development and Per Capita Greenhouse Gas Emissions, PM2.5 Exposure, and Renewable Energy Consumption in Kazakhstan Using the Nonlinear Cointegration (NARDL) Method

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ABSTRACT

This study analyzes the relationships between sustainable development and environmental sustainability indicators in Kazakhstan, specifically focusing on greenhouse gas emissions per capita, PM2.5 exposure, and renewable energy consumption. The Nonlinear Autoregressive Distributed Lag (NARDL) method was employed, which offers distinct advantages by evaluating the separate effects of positive and negative changes and accommodating variables that are stationary at different levels. Using annual data from 1995 to 2022, the analysis revealed that greenhouse gas emissions and PM2.5 exposure have asymmetric and statistically significant effects on sustainable development. Although these effects were found to progress towards equilibrium over the long term, both variables are found to produce significant short-term impacts. However, no significant effect of renewable energy consumption on sustainable development was identified. The study's findings emphasize the need for policymakers to consider the impact of environmental sustainability components on sustainable development. To enhance sustainable development performance, particularly given its low level since 2016, it is vital to implement environmental policies aimed at reducing greenhouse gas emissions and minimizing air pollution from PM2.5. Furthermore, it is suggested that the relationships between environmental sustainability and sustainable development should be examined more deeply, particularly concerning causal structures. Additionally, incorporating the stationarity properties of time series along with structural breaks could provide methodological insights.

Keywords: Renewable Energy Sources, Green Economy, Solar Energy, Wind Energy, Energy Transition, Kazakhstan, NARDL
JEL Classifications: C13, C20, C22

1. INTRODUCTION

The concept of sustainable development is a multidimensional approach that seeks to achieve economic growth in a balanced manner, by taking environmental and social factors into account. This idea was first systematically articulated in the report titled "Our Common Future," published in 1987 by the World Commission on Environment and Development, commonly referred to as the "Brundtland Report." It defines sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). The Brundtland Report established the foundation for the modern understanding of sustainable development, framing it not only as an environmental concern but also as a holistic approach that embraces social justice and economic growth. The United Nations has built upon this framework with the 2030 Sustainable Development Goals (SDGs), which focus on targets such as protecting the environment, using natural resources effectively, and improving the quality of life. In this context, analyzing the relationships between environmental indicators and economic development is vital for sustainability. Indicators like greenhouse gas emissions and exposure to air pollutant particulate matter (PM2.5) present significant risks to both the environment and public health, making them crucial factors in achieving sustainable development goals. Additionally, expanding the use of renewable energy sources is viewed as an effective strategy for reducing environmental degradation and ensuring energy supply security (PAGE, 2020; Aidarova et al., 2024).

Kazakhstan gained independence on December 16, 1991, and began transitioning to a free market economy by implementing comprehensive economic reforms (Sabenova et al., 2024; Yesbolova et al., 2024; Talimova et al., 2025). These reforms involved essential structural changes aimed at ensuring price stability, controlling inflation, privatizing state-owned enterprises, and reforming the monetary system (Sultanova et al., 2024). By the 2000s, these transformations allowed the Kazakh economy to enter a period of stable growth, and the country emerged as a significant economic model among other former Soviet republics (Ibyzhanova et al., 2024; Dyussembekova et al., 2023). Kazakhstan's economy heavily relies on its natural resource reserves, which include approximately 3% of the world's oil reserves, 1.1% of natural gas reserves, and 3.3% of coal reserves (Mudarissov and Lee, 2014; Xiong et al., 2015; Abdibekov et al., 2024; Baimagambetova et al., 2025; Lukhmanova et al., 2025). While these resources support economic growth, they also result in significant environmental costs, leading to increased greenhouse gas emissions and air pollution. The International Energy Agency (IEA, 2023) reports that Kazakhstan's per capita carbon dioxide emissions exceed the global average. Furthermore, PM2.5 exposure levels, as identified by the World Bank, indicate that air quality in Kazakhstan poses a considerable threat to sustainable development goals (World Bank, 2023). According to the PAGE (2020) report, key contributors to the country's environmental pressures include industrial production, energy sector activities, and transportation. However, Kazakhstan has recently begun transforming its energy policies, prioritizing the development of renewable energy sources. Aligned with the "Transition to Green Economy" strategy adopted in 2013, the country aims to increase the proportion of renewable resources in its energy production to 50% by 2050 (PAGE, 2020; URL-1, 2025). This transformation is strategically important for both environmental sustainability and addressing structural issues like energy supply security and economic diversification.

The main objective of this study is to econometrically analyze the relationships between sustainable development, per capita greenhouse gas emissions, PM2.5 exposure, and renewable energy consumption in Kazakhstan. The study employs the nonlinear cointegration method known as Nonlinear Autoregressive Distributed Lag (NARDL) to identify the long-term and potentially asymmetric relationships among the variables. The NARDL model offers a more nuanced approach compared to traditional symmetric models, as it allows for the examination of the effects of positive and negative shocks on the variables separately. This framework enables policymakers to better understand the interactions between the environment, energy, and the economy and to develop more effective strategies. Additionally, this study contributes to the literature by being one of the few that empirically test the asymmetric relationships between sustainable development, environmental quality indicators, and renewable energy consumption in Kazakhstan. Thus, it aims to offer a fresh perspective on sustainability discussions, both for the Central Asian region and for emerging energy-intensive economies.

2. LITERATURE REVIEW

Numerous academic studies have been conducted on the Kazakh economy, particularly on the relationship between sustainable development and environmental indicators in Kazakhstan. These studies employ various econometric and statistical methods, covering different time periods and data sets. Due to space limitations, this summary highlights a selection of key studies that are most relevant to the purpose and scope of this research.

Issayeva et al. (2023) examined the relationships among renewable energy consumption, CO_2 emissions, economic growth, and the industrial production index in Kazakhstan. Their study utilized time series analyses from 1990 to 2021 to investigate the causality and long-term relationships between these variables. The findings indicate that renewable energy consumption effectively reduces CO_2 emissions and supports economic growth. Moreover, a strong positive relationship was found between the industrial production index and economic growth. The study emphasizes the need to strengthen renewable energy policies for Kazakhstan to achieve its sustainable development goals and provides valuable information for policymakers in the energy-economy-environment domain.

Sartbayeva et al. (2023) investigated the relationships between renewable energy consumption, economic growth, and the agriculture-industrial complex in Kazakhstan. Using the ARDL bounds test method with annual data from 1990 to 2020, their findings reveal a positive and significant long-term effect of renewable energy consumption on economic growth. Additionally, the study determined that the agriculture-industrial complex's contribution to economic growth varies over time, with a more prominent effect in the short term. The authors emphasize the importance of developing renewable energy sources within Kazakhstan's sustainable development policies and provide key empirical evidence on the energy-agriculture relationship.

Adambekova et al. (2025) focused on reducing atmospheric pollution as a critical component of the regional circular economy approach in Kazakhstan. The study analyzed the relationship between strategies aimed at minimizing the environmental impacts of industrial activities and sustainable economic development.

The findings indicate that reducing air pollution not only provides environmental benefits but also strengthens circular economic practices at the regional level by enhancing resource efficiency. Drawing on data from various regions in Kazakhstan, the study suggests concrete measures for reusing industrial waste, adopting clean energy technologies, and implementing environmentally friendly policies. Therefore, this study significantly contributes to the literature on integrating environmental sustainability with economic growth.

Smagulova et al. (2025) evaluated Kazakhstan's transition to renewable energy within the context of Central Asia, focusing on economic transformation and environmental impacts from 2000 to 2022. The study analyzed the changes resulting from Kazakhstan's shift from fossil fuels to renewable resources in its energy policy, considering both economic structure and environmental indicators. The findings reveal that investments in renewable energy reduce carbon emissions while increasing economic diversity and energy security. Additionally, the study highlights the structural obstacles and policy deficiencies encountered during this transformation and underscores the need for a comprehensive energy transformation strategy to ensure long-term sustainability. Although focused on Kazakhstan, this analysis offers important implications for shaping sustainable energy policies in Central Asia.

Smatayeva et al. (2024) examined the economic and environmental factors influencing renewable energy consumption in Kazakhstan. Their study evaluated the effects of variables such as income levels, energy prices, environmental awareness, and carbon emissions on renewable energy demand through econometric analysis. The findings indicate that economic growth and environmental concerns positively influence renewable energy consumption. Furthermore, it was found that rising fossil fuel prices incentivize a shift toward renewable energy. The study emphasizes the need to reform Kazakhstan's energy policies from an environmental sustainability perspective and provides scientific insights for strategic planning in the energy transition.

Finally, Tleppayev and Zeinolla (2023) investigates the relationship between CO_2 emissions and economic growth in Kazakhstan, using data from 1999 to 2020. The researchers evaluated the effects of factors such as energy consumption, electricity prices, and the level of urbanization on CO_2 emissions and GDP per capita through regression and correlation analyses. The findings indicate that energy consumption is the most significant factor influencing CO_2 emissions, while energy consumption, urbanization, and energy prices all play equally important roles in the economic growth model. The study emphasizes the need for Kazakhstan to develop low-carbon growth strategies and provides recommendations to policymakers for aligning energy policies with environmental sustainability.

3. METHOD

The NARDL (Non-linear Autoregressive Distributed Lag) method, developed by Shin et al. in 2014, allows for a more detailed examination compared to the ARDL method. A key advantage of this method is its ability to separately test the effects of positive and negative changes. It also accommodates variables that may be stationary at different levels (□(0) or □(1)), similar to the ARDL method.

The Wald test, alongside the Lagrange multiplier test and the likelihood ratio test, is one of three classical approaches to hypothesis testing. One benefit of the Wald test is that it only requires the estimation of the unrestricted model, which lessens the computational effort compared to the likelihood ratio test. Developed by Wald (1943), this test is a multivariate generalization that allows for the simultaneous testing of a series of parameters to determine whether they can be eliminated.

The Wald test is employed to ascertain whether the long-term and short-term coefficients estimated with the NARDL model differ from one another. It evaluates whether the differences between the impacts of positive and negative shocks are statistically significant. If the hypotheses are rejected, that proves the existence of asymmetric relationships between the variables.

Within the NARDL framework, the Bounds Test - developed by Pesaran et al. in 2001 - is utilized to determine whether a long-term relationship exists. The null hypothesis of this test posits that there is no long-term relationship in the model. The F-statistic is calculated as the test statistic and compared against critical values from the Pesaran table. Interpretation of the F-statistic is as follows:

- If it exceeds the upper limit: There is cointegration.
- If it is below the lower limit: There is no cointegration.
- If it falls between the two limits: An unstable situation exists.

Similar to the ARDL method, the lag length in the NARDL method is assessed using the Akaike Information Criterion (AIC), Schwartz Information Criterion (SIC), Log-maximum likelihood (LogL), Bayesian Information Criterion (BIC), and the Hannan-Quinn Information Criterion (HQ).

After establishing the model, its compatibility and goodness-of-fit must be tested. In this context, the Breusch-Godfrey LM test was used to check for autocorrelation, while the White Test and Breusch-Pagan-Godfrey test were applied to detect heteroscedasticity. The Ramsey Reset test, which assesses functional form, was also conducted. Additionally, the structural break in the estimated model was examined using the CUSUM and CUSUMSQ tests developed by Brown et al. in 1975, and the results were presented graphically. The stationarity of the data series was evaluated using the ADF unit root test, where rejection of the null hypothesis indicates that the series is stationary at the relevant level (Dickey and Fuller, 1979).

4. DATA AND FINDINGS

The Sustainable Development Index (SDI) serves as a tool to measure how close countries are to achieving sustainable development goals. It evaluates how nations attain human development while minimizing environmental impact by combining human development indicators - such as life expectancy, education, and income - with environmental factors like ecological efficiency. It is a beneficial tool for comparing countries' progress towards sustainability and assessing their environmental impact.

The two most important tools for achieving sustainable development are planning waste output from production systems to minimize harm to the environment and managing energy consumption within a sustainable framework. Greenhouse gas emissions per capita indicate the total amount of greenhouse gases emitted relative to a country's population. This measurement serves as a crucial indicator for assessing a country's impact on climate change. PM2.5 is used to define pollution levels in both open and enclosed spaces. Particulate Matter (PM) consists of a mixture of solid and liquid particles suspended in the air. These are fine particles that are smaller than 2.5 micrometers in diameter and remain airborne for extended periods. Renewable energy consumption, expressed as a percentage of total final energy consumption, indicates the share of energy derived from renewable sources within a country's overall energy usage. This metric reflects how much of a country's energy demand is fulfilled by renewable sources such as solar, wind, hydro, and biofuels. In Kazakhstan, the management of environmentally harmful waste and the effects of renewable energy use on sustainable development were examined using the NARDL method. The study utilized annual data from 1995 to 2022, sourced from https://data.worldbank.org, https://epi.yale.edu/epi-results/2022/component/epi, and https://www.sustainabledevelopmentindex.org (Access date: 01.03.2025). Table 1 provides the research variables and their brief definitions.

The analysis commenced with descriptive statistics and graphical findings for each variable, illustrating the historical trends of Sustainable Development, Greenhouse Gas Emissions Per Capita, PM2.5 Exposure, and Renewable Energy Consumption in Kazakhstan. Following this, a stationarity examination was conducted as a preliminary step in the research model using the ADF unit root test. Only the stationary series were employed in accordance with the findings. Ultimately, the research model was analyzed, and the results were evaluated.

Table 2 presents the descriptive and distribution statistics for the research variables over the analysis period. The average Greenhouse Gas Emissions Per Capita was calculated to be 10.33, with a standard deviation of 6.491. The median value is 7.68, while the minimum and maximum values are 3.47 and 23.35, respectively, over the 32-year period. The average PM2.5 Exposure was found to be 10.25, with a median of 10.08. The lowest PM2.5 Exposure recorded was 2.39, and the highest was 17.36 during the same period. The average Renewable Energy Consumption stands at 1.80, with a median of 11.80; the minimum and maximum values are 1.10 and 2.80, respectively. The average Sustainable Development Index is reported as 0.53, with a median of 0.56, and the range for this index over 32 years is from 0.30 to 0.69. All four variables are normally distributed according to the Jarque-Bera test statistics.

The temporal changes of the research variables are illustrated in Graph 1 through a time path graph. Greenhouse gas emissions per capita peaked in 1999 at 23.35 but decreased steadily in subsequent years, stabilizing at around 4 since 2007. PM2.5 Exposure showed a continual increase throughout the study period; it started at 2.46 (μg/cm³) in 1995 but surpassed 5.00 (μg/cm³) from 1998 onward, reaching levels that may pose health risks. Renewable energy consumption in Kazakhstan displayed a fluctuating trend, reaching a maximum of 2.80 in 2002 before declining to 1.20 in the following years. The Sustainable Development Index was relatively high, ranging from 0.65 to 0.70 between 1995 and 2004, but has been declining steadily since then, dropping to around 0.30 since 2015.

The preliminary stage of econometric and financial series analysis involves conducting a unit root test to assess the stationarity of the series. Table 3 presents the ADF unit root test findings. At a 5% significance level, it is noted that the industrial production and agricultural production indices are stationary at the level, while oil revenues are stationary at the first difference.

The findings from the bounds test presented in Table 4 are used to assess whether there is an asymmetric cointegration relationship between the variables in the long term. The null hypothesis for this method posits that there is no long-term asymmetrical

Table 1: Variable definitions and sources

Variable	Definition	Source
GASEMS	Greenhouse gas emissions per capita	https://epi.yale.edu/epi-results/2022/component/epi
PM25	PM2.5 exposure	https://epi.yale.edu/epi-results/2022/component/epi
RENGY	Renewable energy consumption (% of total final energy consumption)	https://data.worldbank.org
SDI	Sustainability development index	https://www.sustainabledevelopmentindex.org

Table 2: Descriptive statistics findings for the variables

Statistics	GASEMS	PM25	RENGY	SDI
Mean	10.32643	10.25250	1.800000	0.526321
Median	7.680000	10.08500	1.800000	0.557500
Maximum	23.35000	17.36000	2.800000	0.694000
Minimum	3.470000	2.390000	1.100000	0.296000
Standard deviation	6.491097	4.907537	0.412759	0.155018
Skewness	0.752284	0.130010	0.363640	−0.33724
Kurtosis	2.017936	1.759010	2.752363	1.399576
Jarque-Bera	3.766203	1.875611	0.688638	3.519004
Probability	0.152118	0.391486	0.708703	0.172131

Table 3: ADF unit root test findings for the variables

Variable code	Level		1st difference	
	t- Statistics	P	t- Statistics	P
GASEMS	−0.73879	0.8201	−4.45604	0.0017
PM25	−1.35357	0.5888	−3.09026	0.0398
RENGY	−1.92472	0.3166	−4.56497	0.0013
SDI	−0.16381	0.9320	−5.67802	0.0001
Test critical values				
1% level	−3.69987		−3.71146	
5% level	−2.97626		−2.98104	
10% level	−2.62742		−2.62991	

ADF: Augmented Dickey-Fuller

Graph 1: Time path graph for research variables

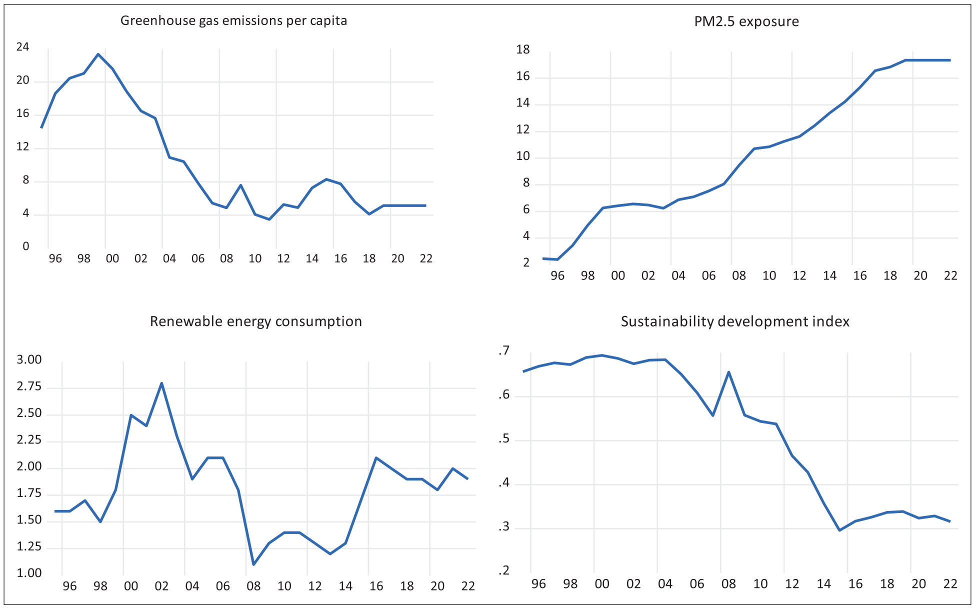


Table 4: NARDL bounds test findings

Test statistic	Value	Significant (%)	I (0)	I (1)
F-statistic	5.729271	10	2.334	3.515
k	6	5	2.794	4.148
-		1	3.976	5.691

relationship among the variables. The results indicate a long-term relationship between oil revenues and the agricultural and industrial production indices. This underscores the importance of thoroughly examining both short-term and long-term relationships of environmental sustainability variables related to sustainable development.

Table 5 provides the NARDL analysis results regarding the relationship between gas emissions, PM2.5 exposure, and renewable energy consumption with sustainable development. When examining the long-term effects of the independent variables, it is observed that positive shocks in both gas emissions and PM2.5 exposure are statistically significant at the 10% significance level. The findings show that a positive shock in both index values (an increase in both index values) has a negative effect on sustainable development (reducing the sustainable development index).

In the short-term analysis, several significant findings emerge. First, the one-period lagged value of sustainable development negatively impacts its current value. Second, the one-period lagged value of a positive shock in gas emissions also negatively affects sustainable development in the short term. As in the long-term findings, positive shocks in gas emissions are expected to decrease sustainable development. Third, the lagged values of positive shocks in PM2.5 exposure, consistent with the long-term effects, also influence sustainable development negatively. As in the case of gas emission, the one-term lagged value of positive shocks in PM2.5 exposure has a negative effect on sustainable development. Furthermore, the analysis reveals that the asymmetric effects

Table 5: Autoregressive distributed lag model and long-term prediction findings

Variable	Coefficient	SE	T-statistic	P
Prediction findings for the model				
C	−0.25618	0.085603	−2.99265	0.0202
DSDI(-1)*	−1.20212	0.211221	−5.6913	0.0007
DRENGY_POS(-1)	−0.08698	0.098923	-0.87928	0.4084
DRENGY_NEG(-1)	0.053836	0.070599	0.762564	0.4706
DPM25_POS(-1)	0.16224	0.070856	2.289713	0.0558
DPM25_NEG(-1)	−0.01424	0.036598	−0.3891	0.7088
DGASEMS_POS(-1)	−0.02571	0.011574	−2.22148	0.0617
DGASEMS_NEG(-1)	−0.01776	0.012005	−1.47967	0.1825
D (DRENGY_POS)	0.017681	0.058957	0.299898	0.773
D (DRENGY_POS(-1))	0.053485	0.062725	0.852684	0.422
D (DRENGY_NEG)	−0.03683	0.049991	−0.73663	0.4853
D (DPM25_POS)	0.149829	0.061749	2.426414	0.0457
D (DPM25_POS(-1))	−0.14957	0.072342	−2.06758	0.0775
D (DPM25_NEG)	−0.01906	0.044626	−0.4272	0.6821
D (DPM25_NEG(-1))	0.050747	0.032779	1.548155	0.1655
D (DGASEMS_POS)	0.003495	0.01014	0.344617	0.7405
D (DGASEMS_NEG)	−0.0054	0.013427	−0.40207	0.6996
Long-Term Prediction Findings				
DRENGY_POS	−0.07236	0.082341	−0.87874	0.4087
DRENGY_NEG	0.044784	0.059373	0.754291	0.4753
DPM25_POS	0.134961	0.061689	2.187778	0.0649
DPM25_NEG	−0.01185	0.0302	−0.39224	0.7065
DGASEMS_POS	−0.02139	0.010019	−2.13486	0.0702
DGASEMS_NEG	−0.01478	0.01027	−1.43888	0.1934
C	−0.21311	0.072098	−2.95579	0.0212

EC=DSDI - (-0.0724*DRENGY_POS+0.0448*DRENGY_NEG+0.1350*DPM25_POS -0.0118*DPM25_NEG -0.0214*DGASEMS_POS -0.0148*DGASEMS_NEG - 0.2131)
SE: Standard error

(positive or negative shocks) of renewable energy consumption do not have a significant impact in either the short term or the long term.

Table 6 presents the findings regarding the NARDL model's compatibility criteria. The Breusch-Godfrey test indicates no autocorrelation problem, while the Breusch-Pagan-Godfrey test shows no heteroscedasticity issues. The Jarque-Bera test confirms that the residuals are normally distributed, and according to the Ramsey RESET test, there is no functional form error in the model.

As with the ARDL model, diagnostic tests for the NARDL model, including the CUSUM and CUSUMSQ tests (following Brown et al., 1975), were conducted to check for structural breaks. Graph 2 shows that the research model does not contain a structural break and yields stable results.

Table 6: NARDL diagnostic test findings

Variables/Tests	Statistics	P
Breusch-Godfrey serial correlation LM test	F-statistic: 0.381232	Prob. F (2.11): 0.6917
Heteroskedasticity test: Breusch-Pagan-Godfrey	F-statistic: 0.378764	Prob. F (16.7): 0.9489
Ramsey reset test	F-statistic: 0.245767	Prob. F (1.6): 0.6377
Test of normality	Jarque-Bera: 0.011401	Prob. 0.994316

Table 7: Findings of the nonlinear autoregressive distributed lag error correction regression model

Variable	Coefficient	SE	T-statistic	P
D (DRENGY_POS)	0.017681	0.023642	0.747883	0.4789
D (DRENGY_POS(-1))	0.053485	0.032279	1.656944	0.1415
D (DRENGY_NEG)	-0.03683	0.021611	-1.70401	0.1322
D (DPM25_POS)	0.149829	0.023525	6.369002	0.0004
D (DPM25_POS(-1))	-0.14957	0.034501	-4.33533	0.0034
D (DPM25_NEG)	-0.01906	0.01573	-1.21201	0.2648
D (DPM25_NEG(-1))	0.050747	0.014584	3.47962	0.0103
D (DGASEMS_POS)	0.003495	0.006056	0.577031	0.582
D (DGASEMS_NEG)	-0.0054	0.006082	-0.88768	0.4042
CointEq(-1)*	-1.20212	0.125557	-9.57436	0
R^2	0.943322	Mean dependent variable		-0.00038
Adjusted R^2	0.906886	SD dependent variable		0.061125
SE of regression	0.018652	Akaike info criterion		-4.83139
Sum squared resid	0.004871	Schwarz criterion		-4.34053
Log likelihood	67.97667	Hannan-Quinn criterion		-4.70117
Durbin-Watson stat	1.646208			

SE: Standard error, SD: Standard deviation

Table 7 illustrates the findings from the NARDL model's error correction form. Unlike the short-term and long-term estimation results in Table 5, negative shocks in PM2.5 exposure also affect sustainable development. Consistent with the findings in Table 5, the effect of the error correction term was found to be statistically significant. The error correction term, which takes values between -1 and 0, suggests convergence toward the equilibrium value. Values between -2 and -1 indicate that the error correction term is oscillating toward the long-term equilibrium value with diminishing size. In contrast, values <-2 or positive reflect a departure from equilibrium (Alam and Quazi, 2003). In this model, the calculated error correction term of -1.20212 suggests that movement towards the equilibrium state is expected in the long term due to shocks in the independent variables. Additionally, the model indicates that 120.21% of the shocks can be eliminated within 1 year, meaning that it takes approximately 0.83 years (about 10 months) to return to equilibrium following a short-term shock.

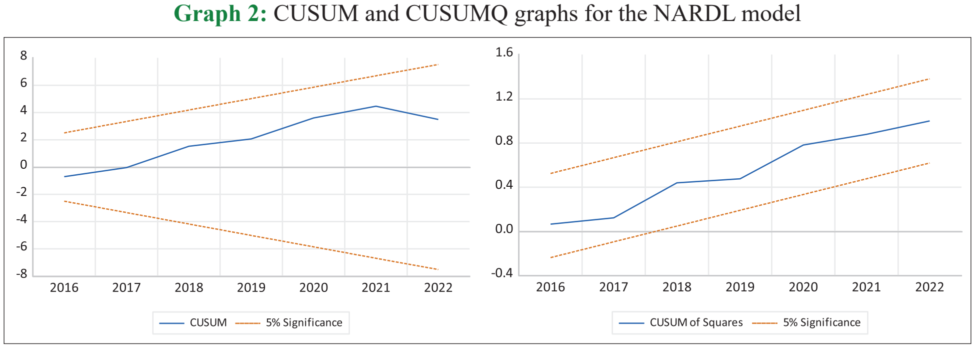
Graph 3 illustrates the asymmetric effect of renewable energy consumption on sustainable development according to the NARDL model. The graph shows that both negative and positive shocks have a greater effect than each individual shock. However, the overall findings presented in Tables 5 and 7 indicate that the impact of renewable energy consumption is not statistically significant.

Graph 4 illustrates the asymmetric effect of new PM2.5 exposure on sustainable development, as determined by the NARDL model. The graph indicates that while positive shocks produce a positive effect, negative shocks have an effect that is approximately zero.

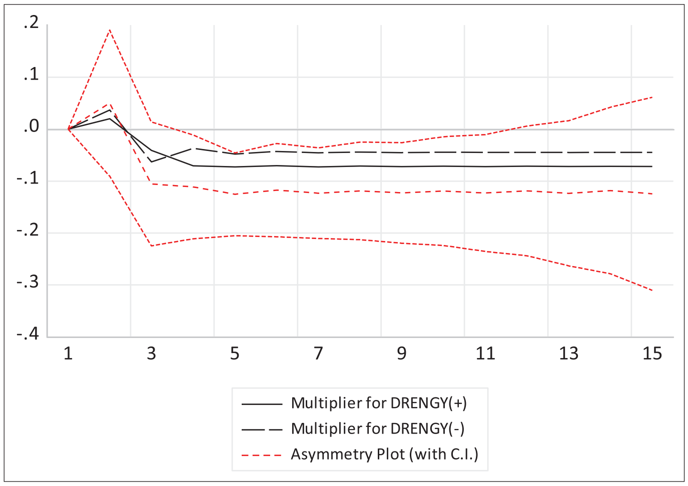
Graph 5 displays the asymmetric effect of gas emissions on sustainable development, as determined by the NARDL model. The graph reveals that positive shocks result in a negative effect, whereas negative shocks generate a positive effect.

Table 8 presents the Wald test findings regarding the asymmetric effects of gas emissions, renewable energy consumption, and PM2.5 exposure on sustainable development. The results indicate that the hypothesis suggesting the same asymmetric effect for all

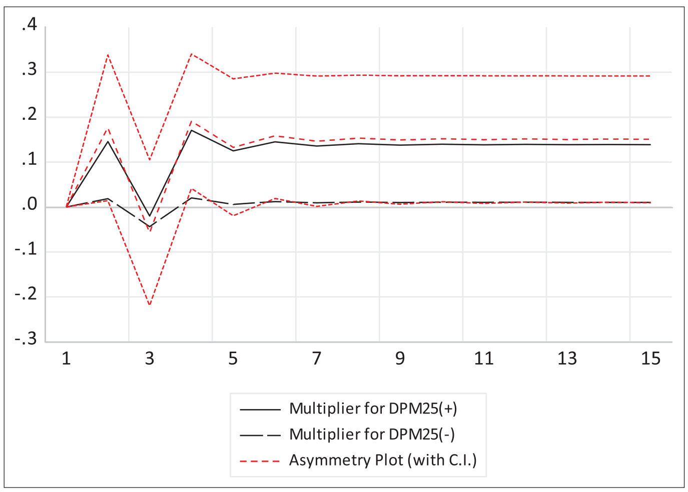
Graph 2: CUSUM and CUSUMQ graphs for the NARDL model



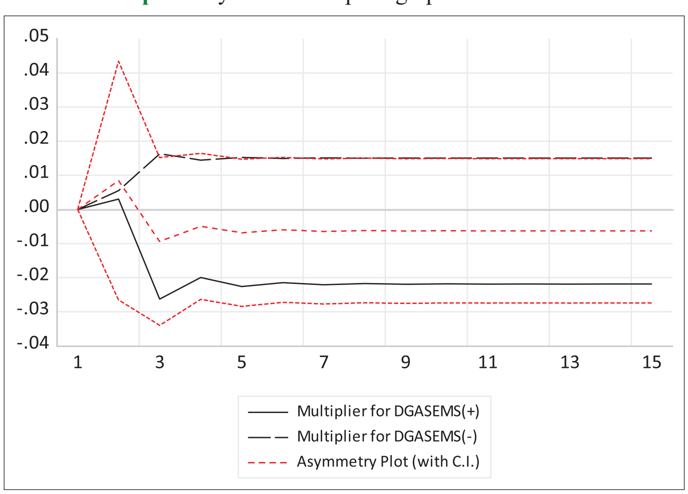
Graph 3: Dynamic multiplier graph for RENGY



Graph 4: Dynamic multiplier graph for PM2.5



Graph 5: Dynamic multiplier graph for GASEMS



three variables - both in the short term and in the long term - could not be rejected. This implies that the independent variables in the model do not exhibit an asymmetric relationship with sustainable development.

Table 8: NARDL model wald test findings

Variable	Chi-square	P
RENGY		
W-SR	2.639253	0.1043
W_LR	1.128010	0.2882
PM25		
W-SR	1.417467	0.2338
W_LR	0.978370	0.3226
GASEMS		
W-SR	1.103846	0.2934
W_LR	0.246737	0.6194

5. CONCLUSION AND RECOMMENDATIONS

This study examined the relationship between environmental sustainability and sustainable development using the NARDL method, focusing on Kazakhstan. An analysis of the changes in the variables throughout the research period shows that renewable energy consumption has a fluctuating yet stable trend. Conversely, gas emissions exhibited a decreasing trend, particularly until 2008, while PM2.5 exposure displayed a consistent upward trend throughout the period. Sustainable development, on the other hand, has shown a declining trend, especially between 2004 and 2016. The model's bounds test findings suggest that a long-term relationship exists between environmental sustainability variables and sustainable development. When assessed individually, it appears that renewable energy consumption does not impact sustainability. However, the long-term effects indicate that positive shocks in PM2.5 exposure have a statistically significant effect on sustainable development. In the short term, both gas emissions and PM2.5 exposure demonstrate significant effects. As a result, it can be concluded that both variables exhibit an asymmetric effect. The error correction model indicates that the relationship between environmental sustainability and sustainable development gravitates towards equilibrium. Thus, it is estimated that any shock to environmental sustainability variables in Kazakhstan will return to equilibrium in less than a year. In summary, the NARDL model reveals that gas emissions and PM2.5 exposure have an asymmetric effect on sustainable development, which trends towards equilibrium. Therefore, it is crucial to make progress in addressing gas emissions and PM2.5 exposure to foster sustainable development, which has been at a low level since 2016.

The findings of this research underscore the need for a more detailed examination of the relationships between environmental sustainability variables and sustainable development. In particular, investigating whether this relationship exhibits a causal structure presents an important research opportunity. Additionally, analyzing the stationarity properties of the variables alongside any structural breaks would significantly enhance the study's effectiveness.

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