# “The importance of renewable energy consumption and $CO_2$ emissions in formulating Sustainable Development Index: An economic-environmental analysis based on the ARDL model”

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# THE IMPORTANCE OF RENEWABLE ENERGY CONSUMPTION AND $CO_2$ EMISSIONS IN FORMULATING SUSTAINABLE DEVELOPMENT INDEX: AN ECONOMIC-ENVIRONMENTAL ANALYSIS BASED ON THE ARDL MODEL

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## Abstract

This study examines the impact of renewable energy consumption, $CO_2$ emissions, and renewable electricity generation on the Sustainable Development Index in Uzbekistan over the period 1990–2023. Using an autoregressive distributed lag (ARDL) model, the study estimates the short- and long-run relationships between these variables. The Sustainable Development Index is constructed using indicators of primary school enrollment, life expectancy at birth, and female labor force participation using a min-max normalization method. The results indicate a long-run positive impact of renewable energy consumption ($\beta = 0.0552$, $p < 0.05$), underscoring its significant contribution to sustainable development. Conversely, renewable electricity generation has a significant negative impact in the long run (–0.0153, $p < 0.01$), which may be due to initial high transformation costs and short-term economic adjustments. $CO_2$ emissions did not have a statistically significant impact on the Sustainable Development Index. The model is robust, with no autocorrelation or heteroscedasticity issues, indicating reliable results. This study underscores the importance of strategic investments in renewable energy and offers valuable insights for policy development, thereby enhancing Uzbekistan's sustainable development trajectory.

**Keywords** renewable energy consumption, $CO_2$ emissions, sustainable development index, economic growth, environmental sustainability

**JEL Classification** Q42, Q56, C32

## INTRODUCTION

Sustainable development has emerged as a key global priority in addressing the interrelated challenges of socio-economic growth, environmental protection, and energy security. Central to this agenda is the shift to renewable energy sources, which is essential for reducing greenhouse gas emissions and strengthening economic sustainability. Renewable energy technologies such as solar, wind, and hydropower not only provide clean alternatives to fossil fuels but are also consistent with the Sustainable Development Goals (SDGs) set by the United Nations, which aim to address issues such as climate change and inequality.

Shifting energy from fossil fuels to renewables is essential for mitigating climate change and increasing energy security. This shift allows energy-dependent countries to reduce their reliance on imported fossil fuels while promoting indigenous renewable energy technologies, thereby contributing to economic sustainability.

Furthermore, improving energy efficiency is a key strategy for this transition, as it allows the same level of service to be provided with less energy consumption, thereby reducing overall emissions and supporting sustainable development.

Along with energy solutions, the circular economy concept plays a crucial role in sustainable development by minimizing waste and enhancing resource efficiency through recycling and regeneration.

This approach not only reduces environmental impacts but also strengthens social equity by ensuring equitable access to resources and opportunities for all individuals. Ultimately, effective environmental policies are essential for integrating these strategies into a holistic framework that supports sustainable development. By prioritizing renewable energy, energy efficiency, and circular economy practices, countries can move toward a more sustainable future that balances economic growth with environmental protection.

Today, sustainable development is one of the main issues on the global agenda, encompassing socio-economic development, environmental protection, and energy security. Renewable energy sources play an important role in this development path, as they provide an opportunity to reduce emissions of environmentally harmful gases and ensure economic stability. In particular, the analysis of renewable energy consumption and its relationship with $CO_2$ emissions is a crucial topic for achieving sustainable development goals in countries.

# 1. LITERATURE REVIEW

The relationship between sustainable development and renewable energy is multifaceted, and numerous studies have identified the positive impact of renewable energy consumption on economic development and sustainability. Renewable energy not only contributes to economic growth but also plays a crucial role in environmental sustainability and social development. For example, studies confirm the causal relationship between renewable energy consumption and value-added in production, as shown in the case of Kazakhstan (Hasanov et al., 2025).

Investment in renewable energy has been shown to significantly boost economic indicators such as GDP growth rates, employment rates, and per capita income in developing countries. Strategic investments in renewable energy infrastructure are essential to ensure sustainable economic growth (Ali & Zaighum, 2024).

Renewable energy production in developed countries is positively correlated with economic growth. For example, a 1% increase in renewable energy production in the G7 countries can lead to an increase in economic growth of approximately 0.70% in the long term (Abubakirova et al., 2024).

Renewable energy innovation and the introduction of green technologies are crucial for sustainable economic growth. Investment in research and development (R&D) for renewable energy significantly contributes to GDP growth and improved environmental performance (Mudaser et al., 2024).

Adopting renewable energy sources reduces ecological footprints and greenhouse gas emissions, ensuring environmental sustainability. Unique sources such as wind energy are effective catalysts for sustainable economic development (Manal, 2024).

The transition to renewable energy sources such as solar, wind, hydropower, and geothermal will help mitigate climate change and contribute to several Sustainable Development Goals (SDGs), making a significant contribution to the universal use of clean energy.

Technological advances in renewable energy, including artificial intelligence and machine learn-


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ing applications, are enhancing energy efficiency and reducing installation and operational costs, thereby supporting environmental sustainability.

Renewable energy consumption is positively associated with improved Human Development Index (HDI), health, education, and economic opportunities. Social benefits also include improving the perception and image of green initiatives, for example, creating a student-friendly environment at the university through the introduction of green technologies (Horváth-Csikós & Juhász, 2024). Effective policy frameworks, such as feed-in tariffs and technological advances, will enhance these benefits (Sharif Zada & Mowahed, 2024). In particular, the study demonstrates how "green" tariffs encourage insurance companies to invest in renewable energy sources, a crucial factor in attracting capital to this sector (Lyeonov et al., 2025).

Renewable energy projects help increase economic opportunities by creating jobs and electrifying villages, which in turn enables inclusive growth in underserved communities. For example, Xolmurotov et al. (2025) show that renewable energy consumption can have a significant impact on unemployment rates, highlighting its social role in Uzbekistan.

The role of renewable energy in supporting economic growth, tourism, and GDP growth is significant, and hydrogen's potential as a clean energy carrier is highlighted.

The relationship between the Sustainable Development Goals and renewable energy consumption can be multifaceted, encompassing economic, environmental, and social aspects. Renewable energy plays a crucial role in achieving several Sustainable Development Goals, SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), by providing sustainable energy solutions that mitigate climate change and promote energy security. The transition to renewable energy is essential to reduce carbon emissions and promote sustainable economic growth, which is consistent with the broader goals of the SDGs.

Renewable energy consumption significantly reduces carbon dioxide emissions, contributes to environmental sustainability, and is consistent with SDG 13. Studies show that renewable energy and institutional quality have a negative impact on consumption-based CO2 emissions, indicating their role in mitigating environmental degradation (Almulhim et al., 2025).

Adopting green technology and renewable energy improves environmental quality by reducing the ecological footprint and supporting the sustainability of ecosystems (Caglar et al., 2024). Renewable energy projects contribute to climate change mitigation by providing clean energy alternatives, which is crucial to achieving SDG 13.

Renewable energy consumption can have varying effects on economic growth, depending on its level of use. In developing countries, it is necessary to exceed a certain threshold of renewable energy consumption to achieve positive economic growth (Ponnambalam & Ilampoornan, 2025).

Technological innovation and renewable energy consumption are positively correlated, stimulating economic growth and supporting SDG 8 (Decent Work and Economic Growth) (Sun et al., 2024). The transition to renewable energy is linked to job creation and economic empowerment, contributing to inclusive growth, especially in rural and underserved communities.

Renewable energy supports social development by improving energy access and infrastructure, which is essential to achieving SDG 7 (Q. Wang et al., 2024). Policy frameworks and international cooperation are essential for overcoming barriers to the adoption of renewable energy sources, including high initial costs and regulatory challenges.

Geopolitical risks and climate policy uncertainties can affect renewable energy consumption, underscoring the need for supportive policies to ensure energy security and sustainable development. Furthermore, the sustainability of utilities, particularly those owned by municipalities, is a key factor in ensuring stable energy supply and resilience to crises, as has been analyzed in the case of Hungary (Lentner et al., 2024).

The link between the Sustainable Development Goals and CO2 emissions is important because many of the SDGs directly address the need to reduce greenhouse gas emissions to combat climate change. The SDGs, particularly SDG 13, demonstrate the need for climate action and significant reductions in CO2 emissions to achieve the broader sustainable development goals (Hariram et al., 2023).

Understanding and managing carbon footprints is crucial to identifying areas where emissions can be reduced and thereby supporting the achievement of these goals (Al-mohannadi & Linke, 2014). Greenhouse gas emissions, primarily CO2, are a major driver of global warming, and reducing them is essential for mitigating climate change and achieving SDG 13.

Effective climate change mitigation strategies, such as switching to renewable energy sources and improving energy efficiency, are essential to reducing these emissions (Rappaccioli-Navas, 2009). Renewable energy sources, including solar and wind, provide clean alternatives to fossil fuels, significantly reduce CO2 emissions, and support SDG 7 and SDG 13 (Jagger et al., 2019).

In addition, introducing a carbon price can create financial incentives to reduce emissions, facilitating progress toward SDG 13. The transition to a low-carbon economy is also important because it minimizes greenhouse gas emissions and supports sustainable development opportunities (Ying et al., 2011). Technologies such as carbon capture and storage (CCS) play a key role in this transition, especially in sectors that are difficult to decarbonize.

Finally, investing in sustainable infrastructure is crucial for reducing environmental impacts, including CO2 emissions, and supports several SDGs, in particular SDGs 9 and 13. Thus, the interlinkages between the SDGs and CO2 emissions justify the importance of integrated strategies for sustainable development.

The link between Sustainable Development Goal 7 and renewable energy generation is essential for achieving a sustainable energy future. SDG 7 aims to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030, which is directly linked to increased renewable energy generation (Senshaw & Edwards, 2020).

Renewable energy sources such as solar, wind, and hydropower are essential for this transition because they provide sustainable and pollution-free alternatives to fossil fuels (Morales Pedraza, 2015). Increasing renewable electricity generation is crucial to expanding energy access, especially in developing countries where energy poverty is widespread. Such access not only improves quality of life but also drives economic growth and poverty reduction.

Decentralized energy systems such as mini-grids play an important role in this context by enabling local energy generation and distribution, thereby reducing dependence on centralized grids (Ohi et al., 1980). Furthermore, effective renewable energy policies and targets are crucial for guiding investment and encouraging the development of renewable technologies (Minji, 2017).

These systems create an enabling environment for innovation and deployment of renewable energy solutions, which are essential to achieving the ambitious goals set out in SDG 7. In addition, energy storage technologies are essential to manage the intermittent nature of renewable energy, ensuring a stable and reliable supply (Xolmurotov et al., 2024). Finally, the integration of renewable energy into existing grid infrastructures poses challenges that need to be addressed to optimize the distribution of renewable electricity.

In conclusion, the interaction between SDG 7 and renewable electricity generation is fundamental to achieving a sustainable energy landscape, promoting economic sustainability, and mitigating climate change.

In the context of Uzbekistan, efforts are underway to expand the use of renewable energy sources, improve energy efficiency, and reduce $CO_2$ emissions. However, there is a lack of in-depth studies that analyze the long-term and short-term impacts of renewable energy use and production on the country's sustainable development index. In this regard, this study is expected to fill the existing gap in this area and contribute to the development of practical policy recommendations.


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## 2. METHODS

The study used the Sustainable Development Index (SDG Index), which is calculated based on three main indicators:

- Primary school enrollment (School enrollment, primary, % gross);
- Life expectancy at birth (Life expectancy at birth, total, years);
- Labor force participation rate, female, % ages 15–64.

The data used in the study cover the period 1990–2023. All data were obtained from the World Bank's open database and Stat.uz and processed for statistical analysis (Table 1).

**Table 1.** Variables, measurements, and sources of data

| Variables | Sources of Data |
|---|---|
| SDG Index (School enrollment, primary (% gross), Life expectancy at birth, total (years), Labor force participation rate, female (% of female population ages 15–64) (mode GDP per capita (current US$)) | World Bank and Stat.uz databases |
| Renewable energy consumption (% of total final energy consumption) | World Bank and Stat.uz databases |
| CO2 emissions (metric tons per capita) | World Bank and Stat.uz databases |
| Renewable electricity output (% of total electricity output) | World Bank and Stat.uz databases |

The min-max normalization method was used to calculate the SDG index. Each indicator was converted to a scale from 0 to 1 and normalized using the following equation:

$$Normalized\,Value = \frac{\left(X_{year} - X_{min}\right)}{\left(X_{max} - X_{min}\right)}, \quad (1)$$

where $X_{year}$ – indicator value for a given year; $X_{min}$ – the lowest value of that indicator between 1990 and 2023; $X_{max}$ – the largest value of that indicator between 1990 and 2023.

It is assumed that all three indicators have equal weight (1/3). The SDG index for each year is calculated using the following equation:

$$SDG\,Index_{year} = \frac{1}{3}\left(Norm\left(School\,Enroll\right) + Norm\left(Life\,Expect\right) + Norm\left(Female\,Labor\right)\right) \quad (2)$$

where *Norm(School Enroll)* – Min-max normalized value of primary school coverage; *Norm(Life Expect)* – Min-max normalized value of life expectancy, *Norm(Female Labor)* – Min-max normalized value of female labor force participation rate.

The study used the ARDL (Autoregressive Distributed Lag) model to analyze the relationship between the SDG index and the following variables:

- Renewable energy consumption (% total final energy consumption);
- $CO_2$ emissions (metric tons per capita);
- Renewable energy production (% total electricity output).

Short- and long-run relationships were identified using the ARDL model. The model results were tested using the following statistical tests:

- Unit root tests (ADF and PP tests) – used to check whether all variables are stationary;
- ARDL Bound test – used to test for long-run correlation;
- Breusch-Godfrey LM test – used to test for autocorrelation;
- Breusch-Pagan test and White test – used to test for heteroscedasticity;
- Ramsey RESET test – used to test for unexpected variables in the model.

The dataset used in this study was previously partially used by Halmuratov et al. (2025a, 2025b). Due to the use of additional variables and new approaches in this study, the reuse of the dataset is justified. All calculations were performed using the statistical software packages Stata 17.0 and R 4.2.2.

# 3. RESULTS

Descriptive statistics play a crucial role in the research process by providing a comprehensive view of the variables used in the study. This approach summarizes and organizes the data, making it easier for researchers and readers to understand the characteristics of the sample and the distribution of the variables. This basic step is essential to ensure that subsequent analyses, such as inferential statistics, are based on accurate and well-understood data. Descriptive statistics are typically used to provide a clear and concise summary of the variables under study (Table 2).

Testing for stationarity is a critical step in time series analysis because it ensures that the statistical properties of the series, such as the mean and variance, remain constant over time. This is essential for accurate modeling and forecasting. The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests are commonly used to assess stationarity (Table 3). These tests help determine whether a time series is stationary or non-stationary. Non-stationary data can lead to spurious results, making it difficult to draw reliable conclusions from the analysis (Van Greunen & Heymans, 2023). Stationarity provides an effective separation of a time series into components such as trend and seasonality, which are necessary for accurate forecasting (Singh et al., 2024).

According to the analysis results, the SDG Index has its own level statistics of –2.300 and –1.807, and *P*-values of 0.1720 and 0.3768, i.e., non-stationary. However, in the first-order difference, it is –5.627 and –6.902, with *P*-values of 0.0000 ($P < 0.05$), i.e., stationary. Renewable energy consumption is not stationary at its own level (–2.474 and –3.373), but stationary at the first-order difference (–4.449 and –7.186, $P < 0.05$). CO2 emissions are not stationary at their own level (–1.356 and –1.350), but stationarity is achieved at the first–order difference (–2.852 and –5.862, $P < 0.05$). Renewable electricity output is also not stationary at its level (–1.547 and –1.829), but there is stationarity in the first–order difference (–4.792 and –10.337, $P < 0.05$).

All variables in the study are not stationary at their level. All variables become stationary after first-order differencing. Methods for estimating long- and short-run relationships, such as the ARDL model, can be used because the data have an I(1) process. To continue the process, first-order differencing of the time series must be used.

Determining the lags of variables is a crucial step in time series analysis, as it helps to understand the temporal dependence and causal relationships between variables (Table 4). Lags represent the time delay between cause and effect in a time series, and determining the correct lag is crucial for accurate modeling and forecasting. Various methods and frameworks have been developed to de-

**Table 2.** Descriptive statistics

| Variable | Obs | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|---|
| SDG_Index | 34 | .4172 | .0547 | .3388 | .5434 |
| Renewable energy consumption | 33 | 1.3154 | .3245 | .72 | 2.1 |
| CO2 emissions | 31 | 4.4115 | .7257 | 3.1744 | 5.7419 |
| Renewable electricity output | 33 | 16.9410 | 3.8270 | 11.1345 | 22.9959 |

**Table 3.** Unit root test results (Intercept)

| Variable name | ADF test | | PP test | |
|---|---|---|---|---|
| | at Level | first-difference | at Level | first-difference |
| SDG_Index | –2.300 (0.1720) | –5.627 (0.0000) | –1.807 (0.3768) | –6.902 (0.0000) |
| Renewable energy consumption | –2.474 (0.1218) | –4.449 (0.0002) | –3.373 (0.0119) | –7.186 (0.0000) |
| CO2 emissions | –1.356 (0.6030) | –2.852 (0.0412) | –1.350 (0.6058) | –5.862 (0.0000) |
| Renewable electricity output | –1.547 (0.5103) | –4.792 (0.0001) | –1.829 (0.3664) | –10.337 (0.0000) |


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**Table 4.** Lag-order selection criteria

| Lag | LL | LR | FPE | AIC | HQIC | SBIC |
|---|---|---|---|---|---|---|
| 0 | –33.0966 | – | .00015 | 2.5883 | 2.6174 | 2.7469 |
| 1 | 19.9823 | 106.16 | .000012* | .00122* | .2965* | .9441* |
| 2 | 34.4787 | 28.993* | .000014 | .1049 | .6365 | 1.8022 |

*Note:* * – optimal lag; Endogenous: SDG_Index Ren_ener_cons CO2_emmis_metric_ton Ren_elec_output.

termine these lags, each with its own advantages and applications.

Table 4 presents the criteria for choosing the lag order. The lag order plays an important role in time series analysis because it helps to identify the relationship and causality between variables. According to the AIC, HQIC, and SBIC criteria, lag 1 was found to be the optimal choice.

This result is important in determining the lag order that can be used in the ARDL model and other time series models. The correct choice of lags increases the accuracy of the results and the reliability of the model.

The ARDL model is a popular econometric tool used to analyze the dynamic relationships between variables, especially when they are combined in different orders. Before applying the ARDL model, it is important to test for cointegration between the variables to ensure that a long-run equilibrium relationship exists. The bounds test, developed by Pesaran et al. (2001), is a widely used method for testing cointegration in the context of ARDL models. This test is particularly useful because it can be applied regardless of whether the underlying variables are pure I(0), pure I(1), or a combination of both, making it versatile for a variety of data sets.

The ARDL bounds test is effective even with small sample sizes, which is often a limitation of other cointegration testing methods. This makes it suitable for studies with limited data (Natsiopoulos & Tzeremes, 2022). The bounds test provides a comprehensive view of the relationships between variables, allowing for the simultaneous assessment of short-term and long-term dynamics.

Although the ARDL bounds test is a reliable tool for testing cointegration, it is important to consider its limitations and ensure that the model is properly specified. Researchers should be aware of the potential for spurious results and may need to use additional methods to confirm their findings (Maji, 2022). Despite these difficulties, boundary testing remains a valuable method for examining long-term relationships across various domains.

Table 5 presents the results of the ARDL (Autoregressive Distributed Lag) bound test. This test is used to determine the presence of long-run dependence (cointegration). $F$-value = 6.075, the $F$-statistic is above the critical values, i.e., at the 1% (4.29–5.61), 2.5% (3.69–4.89), 5% (3.23–4.35), and 10% (2.72–3.77) levels. This is above the I(1) threshold, which means that there is a long-run dependence. $t$-value = –4.522, the $t$-statistic is also below the critical values, i.e. at the 1% ((–3.43) – (–4.37)); 2.5% (–3.13) – (–4.05); 5% (–2.86) – (–3.78); and 10% (–2.57) – (–3.46). This further confirms the existence of a long-term relationship.

These results indicate that the long-run regression results using the ARDL model are robust. The results of the study prove the long-run relationship between renewable energy, $CO_2$ emissions, and the SDG index.

**Table 5.** ARDL bound test results

| Bound Test statistics | | Critical F-values | | Critical t-values | |
|---|---|---|---|---|---|
| Estimated Values | Critical Levels | Lower Bounds | Upper Bounds | Lower Bounds | Upper Bounds |
| – | 0.010 | 4.29 | 5.61 | –3.43 | –4.37 |
| F-value = 6.075 | 0.025 | 3.69 | 4.89 | –3.13 | –4.05 |
| t-value = –4.522 | 0.050 | 3.23 | 4.35 | –2.86 | –3.78 |
| K = 3 | 0.100 | 2.72 | 3.77 | –2.57 | –3.46 |

*Note:* accept if $F$ < critical value for I(0) regressors; reject if $F$ > critical value for I(1) regressors.

**Table 6.** ARDL (2,1,2,3) regression results

| Sample: 1994 | thru 2020 | – | | | Number of obs = 27 |
|---|---|---|---|---|---|
| | – | | | | R-squared = 0.6957 |
| | – | | | | Adj R-squared = 0.4725 |
| Log likelihood = 81.9713 | – | | | | Root MSE = 0.0156 |
| **D.SDG_Index** | **Coefficient** | **Std. err.** | **t** | **P > t** | **[95% conf. interval]** |
| | | | **ADJ** | | |
| | | | **SDG_Index** | | |
| L1. | –.8703 | .1722 | –5.05 | 0.000 | [–1.2373 –.5032] |
| | | | **LR** | | |
| Ren_ener_cons | .0552 | .0223 | 2.47 | 0.026 | [.0075 .1029] |
| CO2_emmis_metric_ton | –.0121 | .0192 | –0.63 | 0.5319 | [–.0531 .0288] |
| Ren_elec_output | –.0153 | .0028 | –5.32 | 0.000 | [–.0214 –.0091] |
| | | | **SR** | | |
| | | | **SDG_Index** | | |
| LD. | .3303 | .1947 | 1.70 | 0.110 | [–.0847 .7454] |
| | | | **Ren_ener_cons** | | |
| D1. | –.0339 | .0147 | –2.31 | 0.036 | [–.0652 –.0025] |
| | | | **CO2_emmis_metric_ton** | | |
| D1. | –.0006 | .0156 | –0.04 | 0.968 | [–.0339 .0326] |
| LD. | .0303 | .0142 | 2.13 | 0.050 | [–.00002 .06073] |
| | | | **Ren_elec_output** | | |
| D1. | .0123 | .0036 | 3.33 | 0.005 | [.0044 .0202] |
| LD. | .0087 | .0032 | 2.67 | 0.017 | [.0017 .0156] |
| L2D. | .0049 | .0023 | 2.16 | 0.048 | [.00005 .0099] |
| _cons | .5682 | .1743 | 3.26 | 0.005 | [.1967 .9398] |

Table 6 presents the results of the ARDL (2,1,2,3) regression model. This model was used to analyze the relationship between the SDG index and renewable energy consumption, $CO_2$ emissions, and renewable electricity generation.

*R*-squared = 0.6957; the model's explanatory power is 69.57%, which is a good result. Adj *R*-squared = 0.4725; the adjusted $R^2$ value is 47.25%, which means that the independent variables affect almost half of the results. Root MSE = 0.0156; the model's estimated error rate is relatively low. Log Likelihood = 81.9713; the logarithmic value of the model's likelihood function.

Long Run Effects (LR) L1. SDG_Index (–0.8703, $P$ = 0.000). The effect of the past SDG index on the current index is negative and statistically significant. This indicates that there is a long-term relationship between the variables. Renewable energy consumption (0.0552, $P$ = 0.026) has a positive effect on the SDG index and is statistically significant ($P < 0.05$). Every 1 unit increase in renewable energy consumption increases the SDG index by 0.0552. The effect of $CO_2$ emissions (–0.0121, $P$ = 0.5319) is statistically insignificant ($P > 0.05$). An increase in $CO_2$ emissions may have a negative effect on the SDG index, but the results are not reliable. Renewable electricity output (–0.0153, $P$ = 0.000) has a negative and statistically significant impact on the SDG index ($P < 0.01$). Increasing the share of renewable energy in electricity generation can reduce the SDG index.

As for short-run effects (SR), D1. Renewable energy consumption (–0.0339, P = 0.036) has a negative and statistically significant effect ($P < 0.05$). In the short run, an increase in renewable energy consumption can lead to a decrease in the SDG index. D1. $CO_2$ emissions (–0.0006, $P$ = 0.968) are statistically insignificant ($P > 0.05$), meaning that $CO_2$ emissions do not significantly affect the SDG index in the short run. D1. Renewable electricity output (0.0123, $P$ = 0.005) is statistically significant and positive ($P < 0.01$). In the short run, an increase in renewable energy production increases the SDG index. LD. Renewable electricity output (0.0087, $P$ = 0.017) and L2D. (0.0049, $P$ = 0.048) are also statistically significant and have a positive effect on the SDG index. Constant term (0.5682, $P$ = 0.005); the intercept value of the model is 0.5682, which is statistically significant.


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Overall, there is a long-term relationship. The ARDL model results indicate a positive long-term impact of renewable energy consumption and a negative impact of renewable electricity generation. $CO_2$ emissions do not have a significant impact on the SDG index in the long or short run.

In the short term, the impact of renewable electricity generation is positive, but renewable energy consumption is having a negative impact.

The model fits well ($R^2$ = 69.57%) and many results are statistically significant.

**Table 7.** Breusch-Godfrey LM test for autocorrelation

| lags(p) | chi2 | df | Prob > chi2 |
|---|---|---|---|
| 1 | 0.017 | 1 | 0.8958 |
| *H0*: no serial correlation | | | |

Table 7 presents the results of the Breusch-Godfrey LM test for autocorrelation. The Breusch-Godfrey LM test is used to test for autocorrelation (Halmuratov et al., 2025a, 2025b). In time series analysis, residual variables can be related to values from previous periods, which can lead to inaccurate model results (King, 1987). If autocorrelation is present, the model estimates may be inefficient and unreliable. If autocorrelation is absent, the residuals of the model are independently distributed, indicating that the model is well-formed (Rois et al., 2012).

Table 7 shows the chi-square statistic (chi²) = 0.017, degrees of freedom df = 1, and *P*-value = 0.8958. Null hypothesis ($H_0$): There is no autocorrelation among the residuals. Alternative hypothesis ($H_1$): There is autocorrelation among the residuals. The *P*-value is 0.8958, which means that $P > 0.05$, which means that one cannot reject the null hypothesis. This means that there is no autocorrelation in the model residuals, meaning that the results are reliable. The model residuals were found to be free of autocorrelation ($P = 0.8958 > 0.05$). This model is well specified, and the residuals are independently distributed, meaning that the model results are reliable. The regression estimates are efficient, and there is no problem of spurious correlation. Durbin-Watson statistic = 1.893043. This value is close to ≈ 2, meaning that autocorrelation is absent or very low. The result is consistent with the Breusch-Godfrey LM test, meaning that the residuals are found to be free of significant autocorrelation.

**Table 8.** Breusch-Pagan/Cook-Weisberg test for heteroskedasticity

| |
|---|
| Assumption: Normal error terms |
| Variable: Fitted values of D.SDG_Index |
| *H0*: Constant variance |
| chi2(1) = 2.58 |
| Prob > chi2 = 0.1083 |

The Breusch-Pagan/Cook-Weisberg test is used to determine whether heteroscedasticity is present (Table 8). Heteroscedasticity is a condition in which the variance of the model residuals depends on the values of the variables, which leads to incorrect estimation and reduced reliability of the regression results (Saribayevich et al., 2024).

Null hypothesis ($H_0$): The residual variance is constant (homoscedasticity exists). Alternative hypothesis ($H_1$): The residual variance is not constant (heteroscedasticity exists). According to the results of the analysis, $chi^2(1) = 2.58$, Prob > $chi^2$ = 0.1083, $P > 0.05$, i.e., one cannot reject the null hypothesis → There is no heteroscedasticity.

Heteroscedasticity was not detected in the model residuals ($P = 0.1083 > 0.05$). The residual variance is stable (homoscedastic), which indicates a high reliability of the model.

**Table 9.** White's test results

| |
|---|
| *H0:* Homoskedasticity |
| *Ha:* Unrestricted heteroscedasticity |
| chi2(9) = 5.27 |
| Prob > chi2 = 0.8099 |

| Cameron & Trivedi's decomposition of IM-test | | | |
|---|---|---|---|
| **Source** | **chi2** | **df** | **p** |
| Heteroskedasticity | 5.27 | 9 | 0.8099 |
| Skewness | 2.23 | 3 | 5270 |
| Kurtosis | 2.42 | 1 | 0.1201 |
| Total | 9.91 | 13 | 0.7009 |

The White test is used to test for heteroscedasticity (non-constant variance of the residuals) (Table 9). Unlike the classic Breusch-Pagan test, this test can also detect nonlinear relationships in variance, i.e., it helps to identify complex heteroscedasticity (Qodirov et al., 2024). Null hypothesis ($H_0$): Homoscedasticity exists (residual variance is constant). Alternative hypothesis ($H_1$): Heteroscedasticity exists (residual variance depends on the variables). If the *P*-value is greater than 0.05, the null hypothesis is not rejected, and heteroscedasticity is not considered to exist. According to the analysis results, $chi^2(9) = 5.27$, $P > chi^2 = 0.8099$, $P > 0.05$, i.e., one cannot reject the null hypothesis → There is no heteroscedasticity. Cameron and Trivedi IM-test results: $Chi^2 = 5.27$, df = 9, $P = 0.8099$ → Statistically insignificant, there is no heteroscedasticity. $Chi^2 = 2.23$, $P = 0.5270$ → Skewness indicates that the distribution of residuals is normal. $Chi^2 = 2.42$, $P = 0.1201$ → The distribution has moderate skewness. The overall test result is $chi^2 = 9.91$, $P = 0.7009$ → The model is homoscedastic, i.e., the residual variance is stable.

**Table 10.** Ramsey RESET test for omitted variables

| |
|---|
| Omitted: Powers of fitted values of SDG_Index |
| *H0*: Model has no omitted variables |
| F(3, 24) = 0.50 |
| Prob > F = 06890 |

The Ramsey RESET test is used to check whether there are important omitted variables in the model (Table 10). If important variables are omitted from the model, the regression results may be incorrect (Christodoulou-Volos & Tserkezos, 2023).

Null hypothesis ($H_0$): There are no omitted variables in the model. Alternative hypothesis ($H_1$): There are omitted variables in the model. According to the results of the analysis, F(3,24) = 0.50, Prob > *F* = 0.6890, $P > 0.05$, i.e., one cannot reject the null hypothesis → There are no significant omitted variables in the model.

The model is well specified, meaning there are no significant omitted variables. The regression results are reliable because all significant variables are included in the model. $P = 0.6890 > 0.05$, indicating that no significant variables are omitted from the model.

## 4. DISCUSSION

This study analyzed the Sustainable Development Index (SDG Index) and its relationship with renewable energy consumption, $CO_2$ emissions, and renewable electricity generation. Based on the ARDL model, short- and long-run relationships were estimated, and the model reliability was checked through significant statistical tests.

In the long run, renewable energy consumption has a positive impact on the SDG index ($P < 0.05$). This result confirms that sustainable energy sources have a positive impact on socio-economic development. Previous studies have also shown that renewable energy has a positive impact on sustainable development factors such as health, education, and workforce employment (Sharif Zada & Mowahed, 2024).

The long- and short-term effects of $CO_2$ emissions are not statistically significant ($P > 0.05$). This result is consistent with some previous studies, but there is some debate that the effects of $CO_2$ emissions may be stronger (T. Wang, 2024). A possible reason is that the country's manufacturing and industrial sectors may have significantly reduced the correlation between $CO_2$ emissions and the sustainability of the SDG index.

In the long run, a negative impact of renewable electricity generation on the SDG index was found ($P < 0.01$). This is an unexpected result, and the transition to renewable electricity may have a negative impact on sustainable development in the early stages (Moinuddin & Olsen, 2024). This result is in part different from previous studies, as most studies have emphasized the positive impact of renewable electricity generation. The reasons for this can be technological transformation costs, as switching to renewable energy can be economically expensive; temporary job losses, as some traditional energy sectors may shrink, which can create uncertainty in the labor market; national energy policy and infrastructure constraints, as renewable energy requires an adapted infrastructure to operate effectively.

Increasing renewable energy consumption will have a positive impact on the SDG index, so governments and investors should introduce more incentive mechanisms to develop this sector. The negative impact of renewable electricity generation may be temporary, so long-term planning and infrastructure investments are important.

The fact that the impact of $CO_2$ emissions on the SDG index was statistically insignificant suggests


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that further research is needed to better understand this relationship.

This paper has several limitations. The study used country-level data. In the future, it may be important to conduct detailed analysis at the regional or local level. The impact of renewable energy on the SDG index may vary across industries. This could be an interesting area for future research. The study only considered three main factors: renewable energy consumption, $CO_2$ emissions, and renewable electricity generation. Future research could include additional factors such as corruption levels, political stability, and economic development levels.

## CONCLUSION

This study aimed to investigate the impact of renewable energy consumption, $CO_2$ emissions, and renewable electricity production on the Sustainable Development Index in Uzbekistan using the ARDL model.

According to the results, renewable energy consumption has a positive and statistically significant impact on the Sustainable Development Index in the long run ($\beta = 0.0552$, $p < 0.05$). This indicates that increasing renewable energy consumption in Uzbekistan makes a significant contribution to the sustainability of socio-economic development. In the short run, however, increasing renewable energy consumption has a negative impact on the sustainable development index (–0.0339, $p < 0.05$), which may be related to the transformational difficulties and economic adjustment costs that arise in the early stages of the transition to renewable energy.

While renewable electricity generation has a positive impact on the sustainable development index in the short term (0.0123, $p < 0.01$), its impact in the long term is negative (–0.0153, $p < 0.01$). This contradictory result can be explained by the complexities that arise when integrating electricity grid infrastructure and management systems with renewable energy sources. $CO_2$ emissions, on the other hand, did not have a statistically significant impact on the Sustainable Development Index in Uzbekistan.

Based on the results of the study, the following conclusions can be drawn. First, increasing the consumption of renewable energy in Uzbekistan is an effective strategy to support sustainable development. Second, the development of renewable electricity generation should be supported by appropriate infrastructure and institutional reforms to ensure it does not negatively impact sustainable development in the long term. Third, a policy to reduce $CO_2$ emissions cannot be the only sufficient measure to achieve Uzbekistan's sustainable development goals.

Future research is expected to explore the regional and sectoral differentiation of renewable energy policies, find the optimal balance between environmental and economic sustainability, and assess the socio-economic consequences of the energy transition in Uzbekistan. Such research will be important for further improving Uzbekistan's national energy strategy and achieving sustainable development goals.

## AUTHOR CONTRIBUTIONS

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