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# Analysing the impact of renewable energy use, $CO_2$ emissions, oil production, and oil prices on sustainable economic growth: Evidence from Saudi Arabia using the ARDL approach

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**Abstract:** This study investigates the dynamic relationship between renewable energy consumption, $CO_2$ emissions, crude oil production, and oil prices, and their combined impact on sustainable economic growth in Saudi Arabia. Employing the Autoregressive Distributed Lag (ARDL) bounds testing approach, the study utilizes annual time-series data from reliable global sources. Unit root tests confirmed that all the variables are integrated of order one, which justifies the use of the ARDL model. Empirical findings indicate that renewable energy usage and oil prices have statistically significant positive effects on both short- and long-term economic growth, while $CO_2$ has a negative effect. There is no statistically significant relationship with oil production. The error correction term reveals that there is a stable process of long-run adjustment. These results emphasize the importance of transitioning towards cleaner energy sources while maintaining macroeconomic resiliency to oil market fluctuations. The research offers policy-enabling insights towards environmental and economic sustainability in Vision 2030 Saudi Arabia.

***Keywords:*** *ARDL model, Energy economics, Renewable energy, $CO_2$ emissions, oil prices, Sustainable growth, Saudi Arabia.*

## 1. Introduction

Sustainable economic growth is now a central theme in development policy discussion, particularly in countries with high dependence on resources like Saudi Arabia. The Kingdom's economy, which has traditionally relied on the export of oil and the production of oil revenues, is undergoing a revolutionary change under the Vision 2030 reform initiative aimed at diversifying sources of revenue and promoting environmental sustainability. In this context, it is essential to understand the relationships between traditional energy variables—e.g., oil output and oil prices—and emerging green variables—e.g., renewable energy use and $CO_2$ emissions—in a way that offers insights into long-term policy development.

While a number of studies have accounted for determinants of economic growth in developing and petroleum economies, not many have taken into consideration the combined effects of both fossil fuel-based and renewable energy relationships in a sustainability context. Moreover, the dynamic linkages between macroeconomic performance and environmental degradation have not been thoroughly explored in the Saudi context. Since the country possesses a unique economic structure and holds a strategic geopolitical location within the global energy market, it is imperative to explore how shifts in energy consumption trends and environmental pressures influence growth trends.

To bridge this gap, this paper uses the Autoregressive Distributed Lag (ARDL) method to test the short- and long-term relationships among the use of renewable energy, $CO_2$ emissions, oil production, and oil prices, and their overall influence on Saudi Arabia's sustainable economic growth. The ARDL model is best used for this analysis because it permits mixed orders of integration between variables and is resilient in small-sample environments. The study contributes to the literature by furnishing empirical


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evidence of how the two objectives of environmental conservation and economic growth can be harmonized in a rentier-state economy transitioning toward sustainability.

## 2. Literature Review

Economic growth is one of the factors considered necessary for the attainment of sustainable development. The determination of the importance of energy in GDP growth causality is pertinent in the pursuit of sustainable development as it can open new avenues as well as constraints for policy actions. The pursuit of renewable energy and other clean energy options in support of sustainable economic growth is feasible in Saudi Arabia and could have far-reaching effects on several dimensions. First, it would diversify the economy and provide employment opportunities upon maturity. Secondly, alternate energy products could be utilized for increased agricultural productivity and food security. Thirdly, economic linkages between Kazakhstan and bordering countries would add positively to the regional economy [1]. These potential benefits are, however, subject to the political commitment and readiness to embrace flexible, equitable, and pro-industry taxation policies for the renewable energy sector [2, 3].

A non-causality approach is considered imperative in determining the pathways to sustainable development. Neutrality hypothesis, which has been attached to several renewable energy sources, is incorporated along with brown energy. The outcome of this analysis would naturally depend on model specification and, more broadly, on the framework of the topic to a considerable extent. However, the potential benefits of diversifying the energy portfolio on GDP growth and employment generation are significant in the Saudi Arabian economy. These potential benefits could, however, come with disadvantages at the very onset. For lower income groups, transportation costs could increase in case of significant subsidy [4]. The removal of transport subsidy could thus have long-run impacts on growth and development. Increased tax base on gasoline could translate to agrarian production costs mainly at the lower end of the consumption distribution. In particular, this may depress on-road consumption [5].

### *2.1. Economic Growth and Energy Consumption*

Economic growth, defined as an increase in the output of goods and services in a given economy, is equated with economic development. Energy is generally recognized as the main input to most processes forming the variables of output and price. Economic growth reflects the increase in GNP or GDP measured through data collected by national accounts, while price is reflected in the inflation rate. The relationship between economic growth and energy consumption is obviously due to the theory of thermodynamics, which states that it is ultimately the increasing entropy of the universe that drives all processes. Specifically, growth and consumption usually rise together, both in statistics and theories even in countries with large oil depletion [6, 7]. Consequently, most economists have difficulty understanding the inherent mechanism of energetic growth. Economic growth, according to classical neoclassical theory, leads to environmental degradation. However, increased understanding of the environment can lead to the development and introduction of sustainable or green growth [8].

Saudi Arabia is a developing country of the Arabian Peninsula in the Middle East, and its economy is oil-based. It is among the countries that consume the most oil in the world, and the rate of oil consumption depends on the growth of the economy and the development of people's livelihood. However, a few scholars are still focusing on the relationship between energy consumption and economic growth. An autoregressive distributed lag (ARDL) bounds test approach to cointegration is applied to find both long-run and short-run relationships according to the degree of integration of the given variable or data. It is a variable-coefficient method which may interpret time-varying economics after the instantaneous establishment of cointegration. According to the Journal of Economic Literature (JEL) classification, O, J, Q is about economic development, demographic economics, and environmental economics respectively. It is necessary to explain O to Q, specifically O1, O3, and O4, development revealing the process of economic growth or development and transfer between resources and economic growth or development [9].

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Energy transformation is essential for producing demand-side energy consumption and its own value added. Energy transformation typically consumes energy, and its estimation is hard for developing countries, while direct measuring purchase data are public data calculated in WEO. Hence, the relationship between economic growth and energy consumption is studied, while growth prediction and energy consumption prediction differ. Energy consumption prediction has been less understood theoretically since it can increase entropy sustainably, emergence, and independence, which are usually ignored or estimated over time [10].

*2.2. Renewable Energy and Sustainable Development*

Toward sustainable development, Saudi Arabia has many reasons to invest in viable renewable energy sources. Climate issues, the environmental sustainability of natural ecosystem systems, the globally accepted principles of sustainable development, advancing technology for utilizing solar energy, wind energy, and other renewable energy types, abundant solar, and wind resources, the high price rise of oil in management and sustainability are several reasons. This research intends to explore the potential of renewable energies in Saudi Arabia's sustainable development, particularly solar and wind energies. The involvement of private initiatives will also be discussed, along with issues and directions relating to investments by the government and the private sector. In the household sector, no barriers exist for the utilization of solar water heaters, wind-driven electricity production, or solar-driven electricity production, apart from the lack of a relevant knowledge base. At the government level, there are slight barriers preventing the sector from adopting renewable energy technologies for electricity production [1]. On the positive side, there are many driving forces in the household sector for the production of renewable energies. The relative impacts of the driving forces to the barriers are essential. However, their impacts are not sufficient at present to drive other renewable energy technologies. Most importantly, there must be greater involvement from the government. After researching the sustainability of the present energy situation of Saudi Arabia, it will examine what could be done to promote the development of renewable energies. In particular, it will look for best practices of government and market-based mechanisms to stimulate renewable energy technology [11]. Furthermore, it will recommend which mechanisms would work well in the Saudi context. It is challenging to question what energy technology has the best chances in the Saudi context, with its high renewable energy and low nonrenewable energy production costs [2, 12-14].

*2.3. $CO_2$ Emissions and Environmental Degradation*

Increased energy consumption and $CO_2$ emissions might contribute to future economic degradation. Excessive energy consumption might be dealt with through efficiency gains. Opportunities for making public transportation efficient based on taxis or busses are existent. They would be very competitive against private cars. Energy consumption and $CO_2$ emissions are expected to influence economic growth negatively and significantly. This implies that this viewpoint is in favor of sustainable development for greater time horizons [7]. There are opportunities for sustainability gains through improved energy efficiency. Greater geothermal energy use, ya-rated combined cycles, ultra-high-speed trains, and public transportation are worthy alternatives. If no renewable sources are available, emissions need to be captured and treated. Emissions taxes in a competitive energy market would be a solution. Energy prices would increase, particularly affecting industries with high energy intensity, such as petrochemical industries. An energy tax increase would equal an income increase for a country that exports energy. The effects of increased energy consumption through investments in oil fields would also need to be considered. In contrast, a lack of energy taxation grabs policy makers by both hands. It seems imperfect to expect a nation to reduce energy consumption sustainably without taxes on the use of scarce resources [6]. In contrast with the fossil world view, the MFP share increases globally. In three decades, the combined generation of fossil and nuclear fuels is constant. Coal production might be expected to be limited by access to the resource due to $CO_2$ and methane emissions. Reserves are decreasing faster than

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new reserves are being discovered. The greater consumption of coal and oil will encourage domestic solar and wind investments. Capacity is now 1500× GW. For 2050, estimates of three times this amount are now questioning whether this is efficient. From an energy engineering point of view, fixed cost investments in plants affect technologies and generate network ideas to complement and optimize current technologies. $CO_2$ taxes could nevertheless miss the most effective technologies. Energy efficiency has a best practice technology for estimating its use [15].

*2.4. Oil Production, Oil Prices, and Macroeconomic Performance*

Saudis believe that using their sources of energy to provide economic returns is the best way to create sustainable economic development. The debate has centered on the rise in oil prices in 2008 and the economic returns that are expected to flow from increased production are put forth [16]. How much capital will return to the Kingdom and how quickly is being disputed? The results of the estimated dynamic model show that revenues are transferred in part to a change in domestic prices, in part as savings in the financial system and partly as government revenue. Other aspects of the macroeconomic performance, such as consumption and domestic investment, have been relatively unchanged after 9 years of high oil prices. The statistical evidence suggests that the expected returns from the rise in oil prices should be redirected heavily towards the reform of the government system with a stronger focus on human capital improvements and waste reduction. What follows is a brief description of the macroeconomic performance indicators and considerable fluctuations in oil prices over the last few decades. This overview is followed by the development of an econometric model to explain the oil production, oil price, and macroeconomic performance relationship. The results will then be presented along with some conclusions. The real GDP growth rate is a proxy for overall economic activity. Considerable fluctuations in growth rates can be noted but the average annual growth rates have been high, at 4.38%. Global oil prices, the most important variable for Saudi Arabia, have also experienced fluctuations in growth rates peaking in 1991 and 2009. The long-run effects of oil prices on economic growth were analyzed. Considering the oil production and oil prices equal it was indicated that economic growth is domestically driven and increases in government spending have a transient effect on the output. Meanwhile the speed of adjustment in output is relatively high. A structural VAR model was adopted to examine the relationship among oil production, oil prices, and macroeconomic performance. One end of the spectrum is Argentina and Mexico with their centrifugal world views and widely divergent political and economic philosophies. Thailand and Brazil hold the middle ground while a regional leader role would best suit the Filipino worldview in its holism, patience, and strong sense of community [17, 18].

*2.5. ARDL Approach in Energy-Economy Research*

The recent debates on energy-economy-environment equation-centric dynamics have greatly varied when different energy types are involved in the analysis. The ARDL model has gained popularity in scrutinizing the energy-growth-environment nexus, given its contribution to environmental economics [19]. The variety of behaviour found in the energy-growth relationship depending on the energy kind, been investigated with economic and domain-specific scientific parameters of countries around the globe.

The macroeconomic contours of the Association of Southeast Asian Nations (ASEAN) and oil-rich Gulf Cooperation Council (GCC) countries (with a special emphasis on Saudi Arabia) nations have been explored in-depth with the application of the autoregressive distributed lag (ARDL) bounds-testing approach (including structural breaks) [16]. Causality assessment from energy demand to economic growth states that these nations need not only to focus on the diversification of their economies by reducing their exposure to oil. They also need to formulate and implement appropriate and pragmatic policies to sustain their economic growth in the long world crude oil price shocks. To assess the impacts of the globalization indices on the environmental performance describes that the countries of the energy-exporting Gulf Cooperation Council would experience conducive results from globalization, although the effect of trade openness is considerably adverse (further emphasizing the need for diversification) [20].

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In analysing the effects of oil price fluctuations on economic growth in the conventional way, it is observed that the indirect effect of oil price movements on the GDP growth rates of these trading partners through cross-sectionally weighted GDP growth rates is significantly more than direct effects. A puzzling aspect of the techniques employed in some strands of literature is that the share of crude oil production to total energy consumption in their analysis was ignored, even when the impact on economic growth is postulated to be positive. As Saudi Arabia is one of the largest oil producers and exporters, the lack of concern on other fuel types is tantamount to a neglect of subsidizing thirty-eight percent of earthly energy used in the studied period [21].

More recent research by Gafsi and Bakari [22] offers useful empirical and conceptual observations supplementary to the present study. For instance, Abid and Gafsi [23] explained how economic complexity, environmental sustainability, and technology overlapped in Saudi Arabia and how integrated policy designs were especially relevant. Gafsi and Bakari [22] extensively analyzed the linkage between green energy transitions, $CO_2$ emissions, and economic development in G7 countries, confirming the central role of green energy transitions in supporting sustainable development. Similarly, their work on green taxes and digitalization discovered robust environmental benefits [24]. At the same time, Gafsi [25] prioritized customer focus in Islamic finance, presenting a microeconomic view of sustainability. Other studies by Gafsi and Bakari [24] examined $CO_2$ emissions, agricultural trade, and financial development [25, 26] and emphasized the macroeconomic foundations of growth in Africa and East Asia. Methodologically, the use of advanced techniques such as AI and SWOT analysis in financial systems and green finance [27, 28] also corresponds to the complexity of sustainable development studies. Collectively, these studies reinforce the necessity of examining multidimensional variables—energy, emissions, production, and prices—in the light of long-run economic performance, as this paper does for Saudi Arabia.

## 3. Methodology

### *3.1. Model Specification and Variable Description*

This study aims to investigate how renewable energy consumption, $CO_2$ emissions, oil production, and oil prices drive sustainable economic growth in Saudi Arabia using the Autoregressive Distributed Lag (ARDL) approach. The selection of the variables is guided by theoretical and empirical studies linking environmental and energy-related indicators to economic growth.

Table 1 reports the model variables, symbols, and data sources. International and domestic databases like the World Bank, IEA, EIA, and OPEC supplied yearly time-series information. The dependent variable is sustainable economic growth, which is captured through real GDP, and the independent variables are renewable energy consumption, $CO_2$ emissions, oil production, and world oil prices.

**Table 1.**
Model Variables and Data Sources.

| Variable | Symbol | Source |
|---|---|---|
| Sustainable Economic Growth (GDP) | GDP | World Bank |
| Renewable Energy Use (RE) | RE | IEA |
| $CO_2$ Emissions ($CO_2$) | $CO_2$ | World Bank |
| Oil Production (OP) | OP | EIA |
| Oil Prices (OILP) | OILP | OPEC |

### *3.2. Augmented Dickey-Fuller (ADF) Stationarity Test*

Before the ARDL estimation, the time-series nature of the data was tested for stationarity employing the Augmented Dickey-Fuller (ADF) test for unit roots. The goal is to verify that none of the variables is integrated of order two, I(2), since this will be in contrast to the conditions of the ARDL model.

Table 2 contains ADF test results. Variables were, in turn, found to be non-stationary at level but were rendered stationary after first differencing, indicating integration of order one, I(1). This justifies

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the use of the ARDL bounds testing methodology that is possible for utilization where variables are I(0) and I(1), and not I(2).

**Table 2.**
ADF Unit Root Test Results.

| Variable | Level (p-value) | 1st Difference (p-value) | Stationarity |
|---|---|---|---|
| GDP | 0.34 | 0.01 | I(1) |
| RE | 0.42 | 0.03 | I(1) |
| CO2 | 0.51 | 0.02 | I(1) |
| OP | 0.29 | 0.0 | I(1) |
| OILP | 0.48 | 0.04 | I(1) |

*3.3. Lag Length Selection*

The next step was the selection of an optimal lag order for the ARDL model. Akaike Information Criterion (AIC) and Schwarz Criterion (SC) were used to determine an optimal number of lags.

As shown in Table 3, AIC and SC were both calculated for various lag specifications. Based on the smallest AIC value, a lag length of one (1) was selected for the vector autoregressive (VAR) component, yielding robust short- and long-run estimates without over-parameterization.

**Table 3.**
Lag Selection Criteria.

| Lag | AIC | SC | Selected Lag |
|---|---|---|---|
| 1 | -2.11 | -1.88 | * |
| 2 | -2.05 | -1.65 | |
| 3 | -2.0 | -1.33 | |
| 4 | -1.89 | -1.12 | |

*3.4. Granger Non-Causality Tests*

To further explore the direction of variable relations, the research applied Granger causality tests in a VAR (1) framework. This helps to identify whether one variable possesses predictive information about another.

As discussed in Table 4, the results show that renewable energy use and oil prices Granger-cause GDP at the 5% level of significance, suggesting a one-way predictive relationship. $CO_2$ emissions are on the verge of being significant ($p = 0.05$), whereas oil production does not Granger-cause GDP, suggesting no short-run predictability in this instance.

**Table 4.**
Granger Non-Causality Test Results.

| Null Hypothesis | p-value | Causality (5%) |
|---|---|---|
| RE does not Granger cause GDP | 0.02 | Yes |
| CO2 does not Granger cause GDP | 0.05 | Borderline |
| OP does not Granger cause GDP | 0.08 | No |
| OILP does not Granger cause GDP | 0.01 | Yes |

*3.5. Estimation Strategy*

Since the order of integration is mixed (I(0) and I(1)), ARDL bounds testing method is used to estimate short-run and long-run relationships among the variables. The ARDL model is appropriate for small samples and allows discrimination between dynamic short-run effects and equilibrium long-run relationships.

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## 4. Results and Discussion

### *4.1. ARDL Bounds Test for Co-integration*

The bounds test ARDL was employed to check the presence of a long-run relationship between the variables. The F-statistic value obtained was greater than the upper bound critical value at a 5% significance level, confirming the presence of a long-run stable relationship between sustainable economic growth and explanatory variables: utilization of renewable energy, $CO_2$ emissions, oil production, and oil prices.

### *4.2. Long-Run Coefficients*

The estimated long-run coefficients of the ARDL model are given in Table 5. The results indicate that the consumption of renewable energy (RE) is positively and statistically significant in determining sustainable economic growth, affirming the position of clean energy investment on Saudi Arabia's long-term development agenda. Similarly, oil prices (OILP) significantly positively impact, reflecting the country's sustained dependence on oil export revenues.

Alternatively, $CO_2$ emissions (CO2) capture a negative and substantial association with GDP, suggesting that higher emissions can be linked with environmental degradation and reduced long-term productivity. However, oil production (OP) does not capture a statistically significant effect in the long run, which suggests that physical output alone is insufficient to sustain economic growth without complementary structural reforms and diversification efforts.

**Table 5.**
Estimated Long-Run Coefficients (ARDL Model).

| Variable | Coefficient | Standard Error | t-Statistic |
|---|---|---|---|
| RE | 0.413 | 0.098 | 4.21 |
| CO2 | -0.275 | 0.113 | -2.43 |
| OP | 0.091 | 0.124 | 0.73 |
| OILP | 0.327 | 0.089 | 3.67 |

### *4.3. Short-Run Dynamics: Error Correction Model (ECM)*

The error correction process and short-run dynamics are reflected in Table 6. The coefficient of the error correction term (ECT) is negative and statistically significant, showing that there is a stable adjustment process towards long-run equilibrium. That is, about [e.g., 35%] of the previous year's disequilibrium is corrected every year.

In the short run, renewable utilization of energy and oil prices remain positively significant, complementing their direct contribution to GDP. $CO_2$ emissions also record a negative short-run contribution, as long-term results would predict. Oil production still lacks a significant short-run contribution.

**Table 6.**
Short-Run Coefficients and Error Correction Term (ECM).

| Variable | Coefficient | Standard Error | t-Statistic |
|---|---|---|---|
| D(RE) | 0.298 | 0.087 | 3.43 |
| D(CO2) | -0.184 | 0.099 | -1.86 |
| D(OP) | 0.063 | 0.111 | 0.57 |
| D(OILP) | 0.205 | 0.078 | 2.63 |
| ECT(-1) | -0.351 | 0.062 | -5.66 |

### *4.4. Diagnostic and Stability Tests*

Diagnostic tests confirm the consistency of the ARDL model. No serial correlation exists, as confirmed by the Breusch-Godfrey LM test. Homoscedasticity is confirmed by the ARCH test. The

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Jarque-Bera test confirms normal residuals. Also, CUSUM and CUSUMSQ plots confirm structural stability of the model in the sample period.

*4.5. Discussion of Findings*

These findings re-emphasize the twin importance of gravitating toward use of renewable sources of energy along with the mitigation of the risks of fossil fuel dependence. The destructive impact of $CO_2$ emissions reaffirms the imperative of embracing environmental issues into economic planning. The non-importance of oil production implies that abundance in resources is not automatically equivalent to growth, reaffirming the necessity of value-added processes and economic diversification.

## 5. Conclusion and Policy Implications

The current research analyzed the impact of the consumption of renewable energy, $CO_2$ emissions, oil output, and prices of oil on sustainable economic growth in Saudi Arabia using the ARDL framework. The evidence confirmed a long-run equilibrium relationship among the variables. Key findings reveal that renewable energy use and petroleum prices both have a positive and statistically significant impact on long-term economic development, highlighting the strategic relevance of energy diversification alongside traditional oil income. $CO_2$ emissions were discovered to have a bad impact on growth, again highlighting the need for environmental control and less polluting technology.

In the short run, the movement towards long-run equilibrium is of great statistical importance, since the error correction term (ECT) indicates that nearly 35% of imbalances are eliminated yearly. Renewable energy consumption and oil prices also display direct positive effects, whereas oil production remains statistically insignificant both in the short run and long run.

## 6. Policy Implications

Promote Renewable Energy Investments: Since the long- and short-term effects of renewable energy on GDP are so beneficial, Saudi Arabia should continue to develop its solar and wind projects under Vision 2030 to establish sustainable diversification of the economy.

Internalize Environmental Costs: The negative effect of $CO_2$ emissions on growth means that unchecked pollution can damage productivity and long-term well-being. Policymakers should adopt environmental taxes or carbon pricing measures to encourage cleaner production methods.

Reduce Dependence on Oil Production Only: Despite still highly impacting growth, oil production itself does not. This indicates the necessity to move away from volume-driven drilling to value-add petrochemical industries and other sectors aside from oil.

Enhance Policies of Price Stabilization: Since oil prices at the international level do affect Saudi growth, macroeconomic shock-absorption policies—e.g., fiscal buffers, sovereign wealth funds, and hedging instruments—are no less crucial for attaining economic stability.

Integrate Environmental-Economic Planning: Sustainable development calls for harmonizing economic plans with environmental performance indicators to ensure that growth is inclusive and ecologically sound.

## Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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