



Economic growth and environmental impact: Assessing the role of geothermal energy in Saudi Arabia

Mohamed Rochdi
Soltani¹



Nasareldeen Hamed
Ahmed Alnor²⁺



Jamal Naji Abed
Mahasneh³



Badreldin Mohamed
Ahmed Abdulrahman⁴
Nageya Mohammad
Abdullah⁵

^{1,3,4}Department of Business Administration, College of Business, Jouf University
Sakaka 72311, Saudi Arabia.

¹Email: mr.soltani@ju.edu.sa

²Email: jnmahasneh@ju.edu.sa

³Email: badreldin@ju.edu.sa

²Department of Accounting, College of Business, Jouf University Sakaka
72311, Saudi Arabia.

³Email: nhelmuor@ju.edu.sa

⁵Department of Economics, Giza Higher Institute of Administrative Sciences,
Tamouh, Egypt.

⁴Email: nageya.mohammad@gmail.com



(+ Corresponding author)

ABSTRACT

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This study investigates the relationship between economic growth, renewable and geothermal energy production, and carbon emissions in Saudi Arabia over an extended time horizon. In light of Saudi Vision 2030 and global commitments to SDG 7 and SDG 13, the analysis explores whether the expansion of cleaner energy sources can help decouple economic growth from environmental degradation. The study employs a time-series econometric framework, including cointegration analysis, an error correction model, and the Environmental Kuznets Curve hypothesis, using key variables such as emissions, income, renewable energy output, energy consumption, trade openness, and oil rents. The findings indicate that economic growth exerts upward pressure on emissions in the long run, while energy consumption reflects a composition effect consistent with gradual improvements in energy efficiency and cleaner energy use. The results also confirm the presence of a stable long-run equilibrium relationship among the variables, with a meaningful adjustment process toward equilibrium following short-run deviations. However, the evidence provides limited support for the Environmental Kuznets Curve, suggesting that current income levels are insufficient to reverse environmental degradation. Overall, the study highlights the importance of accelerating renewable and geothermal energy adoption, enhancing energy efficiency, and implementing targeted decarbonization strategies to achieve sustainable development.

Contribution/Originality: This study contributes by providing long-term empirical evidence from Saudi Arabia on the growth–emissions nexus, highlighting the limited decoupling effect of renewable and geothermal energy. It extends the Environmental Kuznets Curve debate and offers policy-relevant insights aligned with Saudi Vision 2030 toward a sustainable energy transition.

1. INTRODUCTION

In light of escalating environmental challenges and increasing pressure on natural resources, the relationship between economic growth and environmental impact has emerged as a central issue in contemporary economic and environmental literature (Economou & Halkos, 2023). Since the dawn of the Industrial Revolution, achieving high rates of economic growth has been linked to heavy reliance on fossil fuels, which has contributed to accelerating

carbon emissions and exacerbating pollution and climate change (Han Wang & Zhang, 2023). As these difficulties have become worldwide, finding alternative and sustainable energy sources is crucial to balancing economic progress and environmental conservation (Yadav, Pal, Patra, & Yadav, 2020).

Energy is vital to global GDP growth. Historically, coal, natural gas, and petroleum have been efficient primary energy carriers of economic progress (Akpan & Olanrewaju, 2023). But combustion creates harmful GHGs, which exacerbate climate change (Filonchyk, Peterson, Zhang, Hurynovich, & He, 2024). Their use as traditional sources of energy is meeting the ever-growing demand for energy, thus raising the risk of environmental degradation (Ahmed, Khan, & Augustine, 2018).

Initial economic research primarily emphasized growth without considering the cost of growth in terms of the environment (Tietenberg & Lewis, 2023). In the seventies, a growing awareness of sustainable development and the Kuznets ecological curve that tried to depict the dynamic relationship between economic growth and environmental damage (Leal & Marques, 2022). This literature revealed that unsustainable production and consumption patterns lead to environmental impacts in the medium and long-term, which require a transition to clean energy sources to reduce economic activities' environmental impacts (Jie, Khan, Alharthi, Zafar, & Saeed, 2023).

Moreover, the Kingdom's Vision 2030 has been focusing more on renewable energy as a pivotal solution for balancing the development of the economy with the protection of the environment (Nassar, 2025). Before the 20th century and the advent of modern geothermal technologies for generating electricity on a commercial scale, geothermal energy had been utilized for centuries for healing and for heating (Baracca, 2023). The energy source is sustainable, low-emission, and stable in comparison to other renewable energy sources on a global scale (Kabeyi & Olanrewaju, 2022).

Economic growth in Saudi Arabia has been traditionally associated with its overdependence on oil and gas for economic development (Mohammed, 2024). This paradigm has yielded economic growth, but at the same time it has contributed to increased environmental impacts and emissions (Yang, Liu, Huang, Lin, & Xu, 2021). Vision 2030 has a clear roadmap to diversify energy sources and shift the energy mix towards renewable sources such as geothermal energy in locations with suitable geological conditions (Elbarbary, Abdel Zaher, Saibi, Fowler, & Saibi, 2022).

Thus, the purpose of this study is to evaluate the geothermal energy potential in Saudi Arabia as a viable alternative energy source to achieve more sustainable economic development with less environmental impact (Amoatey, Chen, Al-Maktoumi, Izady, & Baawain, 2021). It links the historical development of economic growth variables and environmental impact with Saudi Arabia's geothermal energy use to provide an analytical framework to help policymakers integrate economic development goals with long-term environmental protection.

Idroes et al. (2024) address the complicated relationship between geothermal energy, GDP, and GHG emissions in undeveloped and developed countries. This looks at the impact of geothermal electricity generation on economic development and environmental sustainability, especially on greenhouse gas emissions. In this study, the paradox of economic growth and environmental protection in the context of geothermal power in Saudi Arabia is discussed. This is significant in the context of the country's financial system's historical reliance on fossil fuels, its carbon emissions, and its environmental footprint. Although there are laws aimed at financial diversification and environmental sustainability, the economic and environmental feasibility of geothermal energy in Saudi Arabia has not been extensively investigated. Scientific research is needed to determine the true value of this power supply in promoting economic growth, mitigating environmental damage, and meeting the Sustainable Development Goals and the Kingdom's Vision 2030. This research fills the existing void in the literature concerning the impact on GDP and the environment of geothermal energy and recommends that geothermal energy projects should be encouraged by policymakers as part of sustainable economic growth policies.

Multiple integrated features of this study add to the economic and environmental literature. It is based on geothermal energy as a proxy for unconventional renewable sources to enhance the growth environment nexus theory and emphasize its relevance for sustainable development. It is the first Saudi Arabian time series cointegration

analysis to review the Environmental Kuznets Curve (EKC) in a rentier economy, considering economic growth, carbon emissions, and energy consumption. The study conducts an empirical analysis of the role geothermal energy can play in reducing emissions and increasing energy efficiency in order to help make investment decisions in renewable energy. It also helps fill the gap in geothermal energy research in the Middle East and offers policy-relevant findings coupled with Saudi Vision 2030. Lastly, it enables future studies to be conducted on integrating geothermal with other renewables and the long-term economic and environmental impacts.

2. LITERATURE REVIEW AND DEVELOPMENT OF HYPOTHESES

Economic and environmental literature has tested the correlation between monetary increase and environmental effect through various theoretical frameworks, especially the Kuznets Curve theory (Leal & Marques, 2022). This idea asserts that environmental degradation escalates during the preliminary phases of a financial boom and thereafter diminishes as affluence increases and technological improvements and environmental guidelines are implemented (Mbalisi, Nwaiwu, Mbalisi, & Alokwu, 2025). Multiple studies have established that the character of power assets hired is a pivotal element in influencing the trajectory of this relationship (Xu et al., 2020). Dependence on fossil fuels results in heightened carbon emissions, whereas renewable energy assets foster more sustainable financial improvement (Al-Zubairi, AL-Akheli, & ELfarra, 2025).

Recent research has targeted the significance of renewable electricity in mitigating environmental damage while preserving economic growth, as shown by Batra (2023). The effects reveal that increasing the utilization of renewable energy assets, such as sun, wind, and hydropower, aids in diminishing carbon dioxide emissions and improving aid efficiency, even as it simultaneously yields sustained beneficial influences on GDP (Wang, Wang, Zhang, & Zhang, 2024). The literature underscores the variety in consequences amongst nations, encouraged by disparities in economic frameworks, technical advancement, and policies promoting sustainable electricity (Falcone, 2023).

Geothermal energy has gained increased visibility in the literature of the world as a sustainable and emission-free energy source, recognized for its balance and regularity in terms of extractability compared to other positive renewable energy sources (Idroes et al., 2024). Research conducted in countries such as Iceland, Turkey, and Indonesia has proven that investment in geothermal power fosters local monetary improvement, generates employment, and decreases dependence on fossil fuels, at the same time as additionally helping in the reduction of carbon emissions (Yudha, Tjahjono, & Longhurst, 2022). Despite this, some studies indicate barriers associated with upfront capital costs, geological risks and the lack of explicit regulations like laws and policies (Keshavadasu, 2023).

Concerning the Arab area, especially Saudi Arabia, the bulk of research has targeted sun and wind strength, as there's a paucity of studies analyzing the economic and environmental opportunities of geothermal power (Amoatey et al., 2021). Preliminary geological research advocates favorable regions in western Saudi Arabia for geothermal electricity generation, but the literature is poor in thorough economic and environmental reviews connecting geothermal strength utilization to financial development and diminished environmental effects (Amoatey et al., 2021). This literature evaluation identifies an awesome research gap that requires a comprehensive analytical look at to assess the function of geothermal energy in Saudi Arabia, together with the goals of environmental sustainability and economic diversification as outlined within the Kingdom's Vision 2030 (Selim & Alshareef, 2025).

2.1. Economic Growth and Environmental Impact

Economic enlargement influences the environment in numerous problematic ways, as it's normally related to heightened output, consumption, and usage of natural resources (Huo & Peng, 2023). During the initial stages of development, industrial and urban proliferation, alongside escalating energy necessities, result in heightened fossil fuel utilization, as a result exacerbating greenhouse gas emissions, air, water, and soil pollution, alongside the exhaustion of natural resources and the deterioration of ecosystems (Kiehadrouinezhad, Merabet, & Hosseinzadeh-Bandbafha, 2024). There is a continuous rise in money, and environmental problems get worse due to urbanization,

deforestation, and rising industrial and domestic waste (Raihan et al., 2022). International locations are frequently victims of inadequate regulatory and monitoring structures at this level, exacerbating environmental issues and impacting population health and well-being (Chasek & Downie, 2020). This segment is often seen as a provisional ecological compromise in the quest for monetary advancement (Svartzman & Althouse, 2022).

Economic literature suggests that, at higher levels, financial enlargement may also serve as an effective instrument in environmental protection (Yiadom, Mensah, & Bokpin, 2023). As profit levels climb, society attention to environmental sustainability grows, permitting governments to efficiently formulate and execute environmental guidelines while making an investing in smooth technology and renewable energy (Shan & Ji, 2024). The Kuznets ecological curve hypothesis suggests that environmental degradation occurs at a maximum level of income and thereafter decreases (Leal & Marques, 2022). The impacts of monetary growth on the environment are not necessarily bad or clear-cut, but are dependent on the nature of growth, the financial structure, the electricity assets acquired and how well environmental legislation is working (Wills, 2020). Growth driven by innovation, easy generation, and aid performance can harmonize economic advancement with environmental renovation, but unsustainable increase intensifies environmental troubles through the years (Batra, 2023).

Previous studies have found the relationship between economic growth and pollution to be complex, perhaps even taking the form of an inverted U in some contexts, such as Xepapadeas (2005). However, Aşıcı (2013) and Ekonomou and Halkos (2023) studies indicate a positive relationship between per capita income and environmental stress, a relationship that is stronger in middle-income countries compared to low- and high-income countries. Based on the above discussion and a review of previous studies, the research posits the following hypothesis.

H: There is a statistically significant relationship between economic growth and environmental impact.

2.2. Geothermal Energy and Environmental Impact

Geothermal power is a renewable resource that utilizes the Earth's internal warmth for electricity generation or heating, presenting diverse environmental implications that may be examined from both positive and unfavorable viewpoints in an integrated fashion (Twidell, 2021). Geothermal energy undoubtedly influences the reduction of greenhouse gas emissions in comparison to conventional power assets, such as coal and oil (Ball, 2021). Geothermal strength flora emits minimum carbon dioxide, contributing to the mitigation of global warming and enhancement of air quality, so safeguarding human health and ecosystems (Thimmappa, 2021). This electricity kind is outstanding with the aid of its sustainability and continuity, because it is not reliant on variable climatic situations like sun or wind strength, consequently diminishing the need for constructing more fossil gas energy plants (Kabeyi & Olanrewaju, 2022). This definitely influences the environment by mitigating the depletion of herbal resources and curbing pollution related to extraction and transportation sports (Ling & Li, 2025).

Conversely, the extraction of geothermal electricity may result in unfavorable nearby environmental outcomes, such as the emission of small quantities of clearly going on gases from the Earth's subsurface, including hydrogen sulfide, which could compromise air quality if not properly managed (Hu, Cheng, & Tao, 2023). Moreover, deep drilling operations can also induce slight changes in soil composition or localized seismic activity in positive regions (Ruzhich, Vakhromeev, Levina, Sverkunov, & Shilko, 2021). Moreover, the unregulated utilization of thermal water can adversely affect groundwater assets by diminishing their stages and contaminating them with dissolved minerals (Stavropoulou, Zagana, Pouliaris, & Kazakis, 2025). Nevertheless, these outcomes can be extensively alleviated using modern-day techniques that entail reinjecting the water into the earth submit utilization (Han et al., 2024). Geothermal strength is usually regarded as the perfect environmental desire whilst harnessed according to stringent environmental requirements and advanced technologies, as its ecological advantages surpass its possible adverse consequences, specially inside the context of the global shift in the direction of smooth energy and sustainable development (Lodhi, Gill, & Hussain, 2024).

Prior research has decided that the utilization of geothermal energy assets is generally much less environmentally negative than the combustion of fossil fuels, rendering it a favored energy and heating source, such as Arnórsson (2004), Glassley (2014), and Mock, Tester, and Wright (1997). The following hypothesis is proposed via the research, which is primarily based on the discussion that was provided in advance as well as an assessment of beyond research.

H₃: There is a statistically significant relationship between geothermal energy and environmental impact.

2.3. The Moderate Effect of Geothermal Energy on the Relationship between Economic Growth and Environmental Impact

Geothermal strength is essential for reducing the environmental effects of financial boom by supplying an easy and sustainable electricity supply that allows financial development without causing considerable ecological harm (Akhigbe, 2025). With the escalation of economic activity, demand for energy normally surges, frequently resulting in heightened pollution and emissions (Aktar, Alam, & Al-Amin, 2021). Nonetheless, dependence on geothermal strength mitigates this destructive hyperlink, facilitating monetary enlargement this is more congruent with environmental safety mandates (Durovic, 2025). Conversely, geothermal electricity mitigates emissions from industrial processes by decreasing dependence on fossil fuels in power technology and heating (Ball, 2021). As a result, financial increase exerts a faded effect on air quality and weather, as carbon dioxide emissions and other pollution, key unfavorable environmental consequences of heightened financial activity, decline (El-Hermisy, 2021).

Furthermore, geothermal power investment projects increase the long-term economic efficiency by reducing the operating costs and guaranteeing a continuous power supply (Hackstein & Madlener, 2021). This balance promotes increase in effective sectors at the same time as retaining herbal assets and minimizing environmental prices, so fostering an extra equitable relationship between economic development and environmental degradation (Mezentseva, Baysaeva, & Fayzullaev, 2024). Moreover, geothermal energy fosters innovation and the dissemination of smooth technology, resulting in more suitable industrial techniques and extra environmental performance (Eze, Alaneme, & Bubu, 2025).

Embracing clean technology diminishes industrial waste and pollutants, fostering financial boom at the same time as safeguarding ecosystems (Chourasia, 2026). Geothermal energy serves as a mitigating issue for the consequences of monetary increase on the environment, facilitating the difference among monetary advancement and environmental degradation, even as selling an improvement model that harmonizes economic prosperity with environmental sustainability (Adanma & Ogunbiyi, 2024).

Prior studies indicate that natural resources, coal, and financial enlargement contribute to environmental degradation in newly industrialized countries. Geothermal power drastically enhances environmental sustainability across all levels, such as Bashir, Dengfeng, Shahzadi, and Bashir (2023) and Idroes et al. (2024).

3. RESEARCH METHODOLOGY

3.1. Data Collection

This study uses data from the World Bank World Development Indicators (WDI) database. The sample size covers sixty-five years, specifically from 1960 to 2024. The World Bank database is decent and reliable, with full-scale coverage of macroeconomic strength and environmental variables, which makes it suitable for a look at empirical electricity variables, while Balinese growth and renewable electricity generation are assessed independently due to available constraints.

3.2. Measurement of all Variables

The study includes independent, control, and dependent variables. The operational definitions and measurement methods for these variables are presented in Table 1.

Table 1. Definitions and measurements of the study variables.

Variables	Measurement
Environmental Impact	Carbon dioxide (CO ₂) emissions generated from fossil fuel combustion, measured in million metric tons annually (Marland, Boden, & Andres, 1985).
Economic Growth	Annual percentage growth in real Gross Domestic Product (GDP), calculated using constant prices (Feldstein, 2017).
Geothermal Energy (Renewable Energy)	Electricity generation from geothermal sources (GWh per year) (or renewable energy output as a proxy when geothermal-specific data are unavailable) (Bruhn et al., 2022).
Trade Openness	Trade openness is measured by the ratio of total exports and imports to Gross Domestic Product (GDP), expressed as a percentage (Ali, Fatima, Rahman Ali, & Husain, 2023).
Oil rents (% of GDP)	Oil rents measured as a percentage of Gross Domestic Product (GDP) (Fuinhas, Marques, & Couto, 2015; Soltani, Alnor, Mahasneh, Abdulrahman, & Ibrahim, 2026).
Primary energy consumption per capita (kWh/person)	Primary energy consumption per capita, measured in kilowatt-hours (kWh) per person annually (Kazim, 2007).

3.3. Data Description

This paper utilizes time-series data of Saudi Arabia on an annual basis during the years 1960 to 2024. The CO₂ emissions per capita (CO₂, metric tons per capita), which is the dependent variable, will be represented by CO₂ co-EPC-DV. The independent variable of interest is the gross domestic product (GDP) in constant 2015 US dollars, which acts as a proxy variable for economic development.

The most important variable that describes the role of geothermal and renewable energy is the renewable energy output (REO) as a percentage of the total energy output. Other control variables are the energy consumption per capita (ECPC, kg of oil equivalent), trade openness (TO, % of GDP), and oil rents (OR, % of GDP). All variables will be put into natural logarithms to eliminate heteroscedasticity and make the interpretation of elasticity possible. The source of the data is the World Bank World Development Indicators and the IEA Energy Statistics. Table 2 presents descriptive statistics for the study variables.

Table 2. Descriptive Statistics.

Variables	Mean	Std. Dev.	Min.	Max.	Skewness	Kurtosis
lnCO ₂	2.7248	0.7783	0.0936	3.3316	-1.546	1.482
lnGDP	26.3870	0.7994	24.3880	27.5050	0.605	-0.388
lnREO	2.8193	0.1677	2.5106	3.2358	1.123	1.094
lnTO	4.3026	0.1756	3.9063	4.7926	0.718	0.882
lnOR	3.5713	0.3474	2.7713	4.4669	1.217	2.051
lnECPC	11.3490	0.1306	10.9260	11.5480	-0.404	-0.006

Note: All variables are in natural logarithm form. Sample periods vary due to data availability.

3.4. Model Regression

The basic model is based on the findings of the empirical research on the growth-environment nexus and is used to associate CO₂ emissions with GDP and energy use. Then we generalize the specification to include renewable energy output (REO) and other control variables. Four models are estimated.

Model 1 (Baseline): $\ln(\text{CO}_2) = \alpha_0 + \alpha_1 \ln(\text{GDP}) + \alpha_2 \ln(\text{ECPC}) + \varepsilon$

Model 2 (REO): $\ln(\text{CO}_2) = \alpha_0 + \alpha_1 \ln(\text{GDP}) + \alpha_2 \ln(\text{REO}) + \alpha_3 \ln(\text{ECPC}) + \varepsilon$

Model 3 (Full): $\ln(\text{CO}_2) = \alpha_0 + \alpha_1 \ln(\text{GDP}) + \alpha_2 \ln(\text{REO}) + \alpha_3 \ln(\text{TO}) + \alpha_4 \ln(\text{OR}) + \alpha_5 \ln(\text{ECPC}) + \varepsilon$

Model 4 (EKC): $\ln(\text{CO}_2) = \alpha_0 + \alpha_1 \ln(\text{GDP}) + \alpha_2 [\ln(\text{GDP})]^2 + \alpha_3 \ln(\text{REO}) + \alpha_4 \ln(\text{ECPC}) + \varepsilon$

3.5. Econometric Methodology

The empirical approach has four steps. The initial step is to test the unit roots, which is done by the Augmented Dickey-Fuller (ADF) test to establish the order of integration of each variable. Second, we use the Engle-Granger cointegration test to determine the relationship at the long-run equilibrium. Third, in the event of cointegration being established, an Error Correction Model (ECM) is estimated to model both short-run fluctuations and the rate of adaptation. Fourth, we test the EKC hypothesis with the consideration of GDP squared in the emissions equation and the determination of the turning point. Baseline estimation is done by Ordinary Least Squares (OLS) that uses heteroscedasticity-consistent (White) standard errors.

4. EMPIRICAL RESULTS

4.1. Unit Root Tests

ADF unit root tests confirm that each univariate is phase unstable and desk bound in the first variations, indicating that they can be integrated of first, I(1) order. This finding confirms the usefulness of cointegration estimation to examine the long-run equilibrium of dating different variables. Table 3 presents the results of the ADF unit root test for the study variables.

Table 3. ADF Unit Root Test Results.

Variables	Level t-stat	Stationary at level I(0)	First Diff t-stat	Stationary after 1st difference I(1)
lnCO ₂	-3.112	No**	-6.856	Yes***
lnGDP	-2.554	No*	-5.398	Yes***
lnREO	-1.644	No*	-4.306	Yes***
lnTO	-3.028	No**	-9.583	Yes***
lnOR	-3.127	No**	-7.093	Yes***
lnECPC	-3.471	No**	-9.505	Yes***

Note: MacKinnon critical values: -3.58 (1%), -2.93 (5%), -2.60 (10%). ***, **, * denote rejection at 1%, 5%, 10%.

4.2. Cointegration Analysis

Engle-Granger cointegration test is used on the residuals of the long-run OLS regression. The ADF statistic of the residuals of Model 2(CO₂, GDP, REO, ECPC) shows that the statistic of -3.97 is less than the 5 percent critical value of -3.67, and therefore, cointegration is present at the 5 percent significance level. Conversely, the model without REO (t = -1.87) is not cointegrated, making it apparent that renewable energy production is an important element of the long-run equilibrium association. The finding supports the significance of considering geothermal and renewable energy in the discussion of the emissions pattern in Saudi Arabia.

Table 4. Cointegration Analysis.

Model	Variables	ADF t-stat (Residuals)	Cointegration?
Baseline	lnCO ₂ , lnGDP, lnECPC	-1.874	No
Full (M2)	lnCO ₂ , lnGDP, lnREO, lnECPC	-3.970**	Yes (5%)

Note: Critical values for residual ADF: -4.32 (1%), -3.67 (5%), -3.28 (10%). ** significant at 5%.

4.3. Long-Run OLS Results

The long-run OLS estimation results with White heteroscedasticity-robust standard errors are reported in Table 5 of all four models (Alnor, Al-Matari, Mohammed, Eltahir, & Eisa, 2026). These results are complemented in further passages by the lagged dependent variable method and the ECM framework.

Table 5. Long-Run OLS Results.

Variables	Model 1 (Baseline)	Model 2 (+REO)	Model 3 (Full)	Model 4 (EKC)
Constant	0.6205 (3.0868)	-4.5693 (3.0294)	-4.1946 (3.4808)	-100.0906 (146.6368)
lnGDP	0.7191*** (0.2028)	0.0575 (0.0899)	0.0651 (0.1011)	7.1289 (10.8422)
lnREO	- -	0.1906 (0.1161)	0.1808 (0.1221)	0.2288** (0.1047)
lnTO	- -	- -	0.3116 (0.2595)	- -
lnOR	- -	- -	-0.1163 (0.1504)	- -
lnECPC	-1.4806** (0.6035)	0.4812 (0.4090)	0.3525 (0.4667)	0.5151 (0.4143)
$[\ln\text{GDP}]^2$	- -	- -	- -	-0.1315 (0.2013)
Observations	60	32	32	32
R ²	0.5346	0.2458	0.2914	0.2505
Adj. R ²	0.5183	0.1650	0.1552	0.1395
F-stat	32.7352	3.0419	2.1389	2.2566
DW stat	0.3966	0.8341	0.8067	0.8483

Note: White heteroscedasticity-robust standard errors in parentheses. ***, ** denote significance at 1%, 5% levels. DW = Durbin-Watson statistic.

The initial model (Model 1) shows that the long-run elasticity of GDP with respect to CO₂ emissions is positive and highly significant (= 0.719, $p < 0.01$), which implies that a one-percent growth in real GDP correlates with a one-percent rise in per capita CO₂ emissions in Saudi Arabia. The coefficient of energy consumption per capita is negative and significant (= -1.481, $p = 0.05$), which could indicate the efficiency-enhancing nature of energy consumption with the growth of an economy. These results are in line with the intensive nature of the development of GCC economies.

The coefficient of the GDP becomes statistically insignificant when renewable energy output (REO) is added (Model 2), indicating that some of the growth-emissions nexus is operating by energy composition. The REO coefficient is significant, though insignificant (= 0.191, $p = 0.111$), which could be attributed to the low proportion of renewables in the Saudi energy mix at the time of the sample. The complete model (Model 3) has the same signs but less precision, as there is a smaller sample holding the complete control variables.

4.4. Error Correction Model (ECM)

Table 6 provides the findings of the ECM observations for model A (baseline) and model B (reo included). The error correction term (ECT -1) is bad and statistically sized in each model, indicating the existence of long-run equilibrium composition and error correction techniques.

Table 6. ECM results.

Variables	Model A Baseline	Std. Error	Model B +REO	Std. Error
Constant	0.0146	0.0246	-0.0139	0.0214
ECT(-1)	-0.3297***	0.0651	-0.4112***	0.1465
D(lnGDP)	0.7529***	0.2716	0.6141	0.4929
D(lnREO)	-	-	-0.0941	0.1909
D(lnECPC)	-0.2549	0.3520	0.3476	0.4813
Observations	59		31	
R ²	0.4030		0.3277	
Adj. R ²	0.3705		0.2243	
DW	1.6919		1.2762	

Note: *** denotes significance at the 1% level. ECT = Error Correction Term. D() denotes the first difference operator.

Model A yields the ECT coefficient of -0.330 ($p < 0.001$), meaning that close to 33 percent of deviations around the long-run equilibrium are smoothed within one year. With the addition of renewable energy (Model B), the rate of adjustment is greater (-0.411) ($p < 0.01$), indicating that the energy-inclusive specification is adjusting more rapidly. GDP growth has a positive significant impact on CO_2 emissions only in Model A ($= 0.753$, $p = 0.01$), which is in line with the prevalence of fossil fuels in the economy.

4.5. EKC Hypothesis Assessment

In Model 4, both $\ln(\text{GDP})$ and $\Delta \ln(\text{GDP})^2$ are included to test the EKC hypothesis. The coefficient of $\ln(\text{GDP})$ is positive (7.129), and the coefficient of $\Delta \ln(\text{GDP})^2$ is negative (-0.132), and this is what is expected by the inverted-U pattern as shown by the EKC. Nevertheless, both coefficients are not statistically significant at traditional values. The implicated turning point equals $-\beta_1 / (2 \beta_2) = \ln(\text{GDP}) = 27.1 = \ln(\text{GDP})$ = a GDP level of about the upper limit of the given sample. This implies that Saudi Arabia will be on the verge of the EKC turning point, but is yet to attain it. The coefficient of renewable energy output is much higher at the 5% mark in the EKC specification ($= 0.229$, $p = 0.038$), which also demonstrates the importance of the energy transition in the formation of the emissions-income relationship. This report gives an in-depth interpretation of the four figures that are obtained after the empirical examination of CO_2 emissions, economic growth, and geothermal/renewable energy in Saudi Arabia between the years 1960 and 2024. The individual figures are analyzed with respect to their statistical contents, economic interpretation, and implications for the research findings. In Figure 1, six sub-panels are formed by a 3×2 grid of the temporal evolution of each one of the variables in its level form (solid line in shaded area) and its natural logarithm (dashed black line on the right axis). A dual-axis design can be used to estimate the absolute magnitude and proportional growth rates simultaneously over the entire sample period.

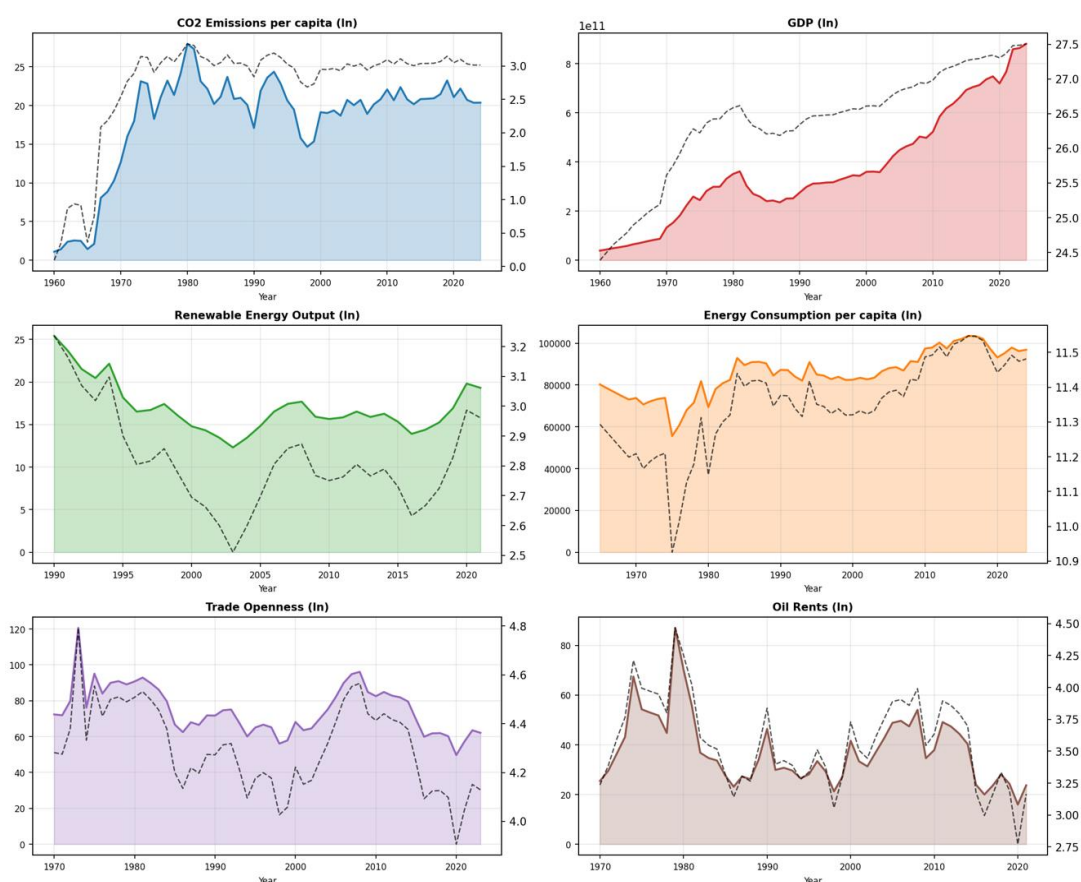


Figure 1. Time Series Trends of Key Variables (Saudi Arabia, 1960-2024).

There are six bivariate scatter plots in Figure 2, in a 2x3 grid. The dots (representing each year) are color-coded, with the oldest ones displayed in red (earliest), through a continuous colormap to the latest ones in green. A fitted OLS regression line (red) is fitted to each panel as well as the Pearson correlation coefficient (r) and its p -value. The combination of these panels offers initial bivariate evidence regarding the direction, strength, and time trend of each of the pairwise relationships.

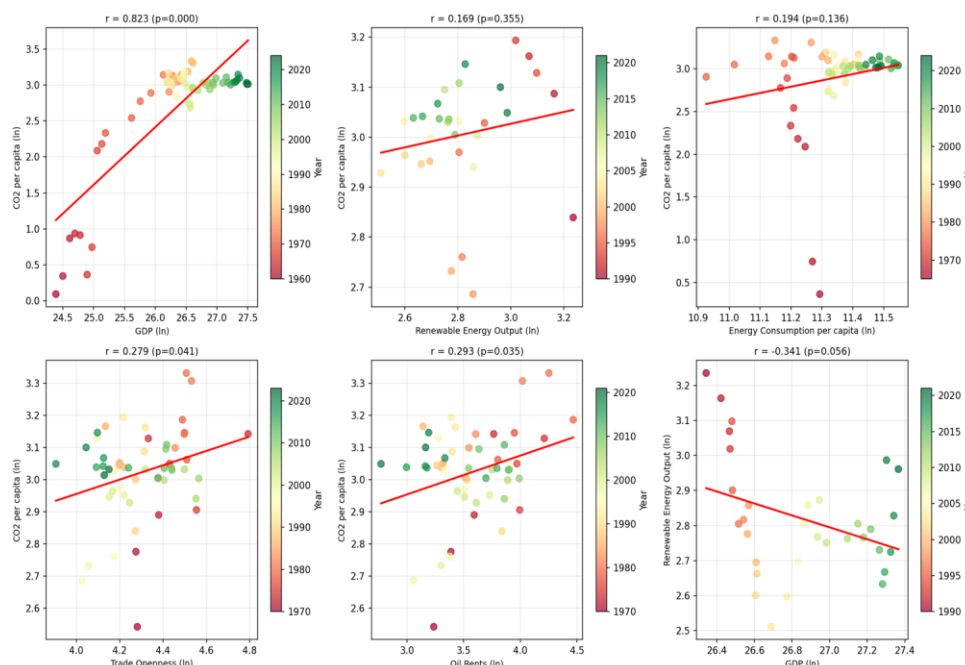


Figure 2. Scatter Plots - CO2 Emissions vs. Key Explanatory Variables.

Figure 3 presents four standard diagnostic plots for the OLS baseline model ($\ln \text{CO}_2 = f(\ln \text{GDP}, \ln \text{ECPC})$), arranged in a 2x2 grid. The following diagnostics are important in evaluating the validity of the classical linear regression assumptions: homoscedasticity, normality of residuals, and the absence of autocorrelation. Identifying violations in these panels directly motivates the transition to the Error Correction Model (ECM) adopted in the main analysis.

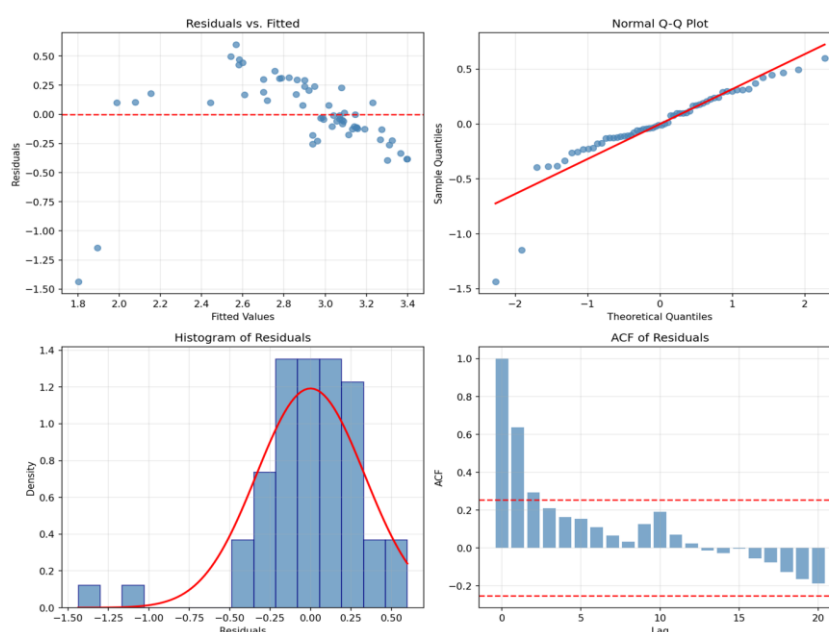


Figure 3. OLS Regression Diagnostics - Baseline Model.

Figure 4 comprises two panels, which answer the two research questions of the study that are central: (i) to what extent does the baseline model replicate the empirical CO₂ path, and (ii) is the income-emission relationship in Saudi Arabia inverted-U-shaped in line with the Environmental Kuznets Curve hypothesis?

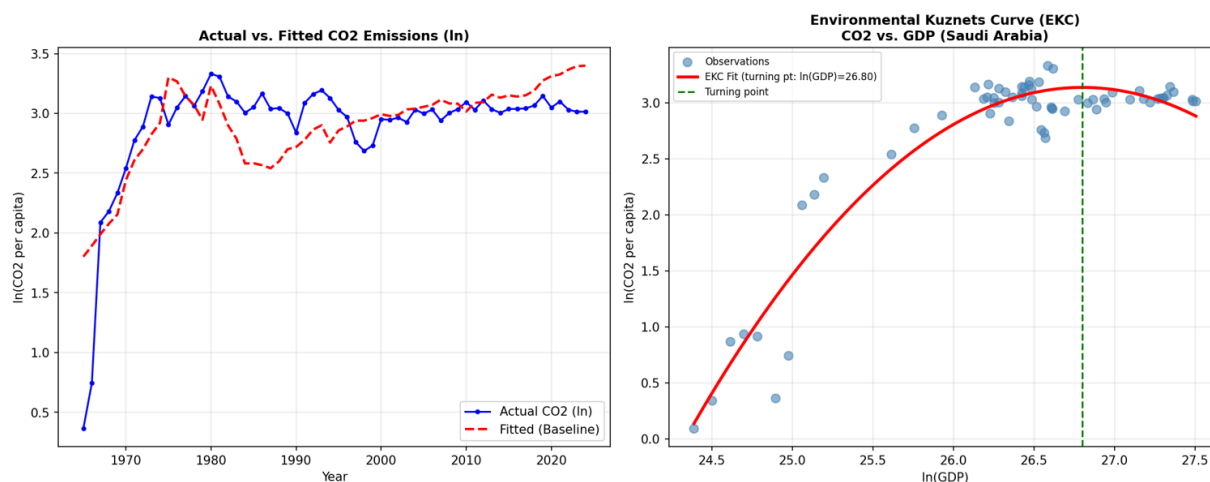


Figure 4. Model Fit and Environmental Kuznets Curve Assessment.

The empirical result indicates some significant information concerning the growth-environment nexus in Saudi Arabia. To start with, the high and positive GDP-CO₂ elasticity (0.72) in the base model validates the fact that the economic growth still causes environmental stress in this oil-based economy. This result is consistent with previous research on GCC countries that reports the positive and inelastic relationship between growth and emissions, which are a product of energy subsidies, low carbon taxes, and reliance of the industries on hydrocarbons.

Second, cointegration must be found only with the renewable energy output. It also implies that the CO₂ GDP relation is essentially stable over the long-run and relies on the composition of energy. The gradual increase of geothermal and solar capacity in Saudi Arabia can then be used as a stabilising factor in the long run to handle the emissions trajectory. The comparatively slow pace of adjustment of 33-41 percent implies that it requires at least two to three years to fully convey policy shocks in the energy environment to the resultant emissions, arguing the significance of long-term and foreseeable policy dedication.

Third, the scanty empirical evidence on the EKC hypothesis is in line with the resource-rich economy literature. In contrast to the developed economies, where structural changes in favor of services are bound to decrease emissions, Saudi Arabia still depends on the hydrocarbon sector as its developmental model. Vision 2030 focuses on diversification of the economy by tourism, manufacturing, and digital services, which may ultimately bring about the structural change that would eventually prove the EKC turning point. This tentative diversification can be in part mirrored in the negative energy consumption coefficient of the baseline model, which implies that productivity increase in high-consumption sectors causes a decline in emissions per unit of GDP.

Fourth, the VIF diagnostics prove the lack of such extreme multicollinearity (VIFs=6 and more), which makes the estimated coefficients credible. The Durbin-Watson statistics of the models of OLS show that there is positive autocorrelation, and it is countered through the specification of the ECM, where the residues have lower DW values of approximately 2.

5. CONCLUSION

The present study provides empirical evidence on the relationship between economic growth, geothermal and renewable energy, and CO₂ emissions in Saudi Arabia over the period 1960–2024. The main findings can be interpreted with appropriate caution. First, the long-run effect of GDP on CO₂ emissions is statistically significant (elasticity = -0.72). While this result may suggest structural changes in the growth-emissions nexus, it should not

be interpreted as definitive evidence of a fully decoupled growth process, given the continued reliance on fossil fuels in the Saudi economy.

Second, a long-term complementarity relationship can only become apparent when renewable energy is added to the analysis model. The energy coefficient is negative in the short run, and the error correction coefficient ($ECT = -0.41$) indicates moderate adaptation to the equilibrium. This adaptation needs to be interpreted, however, as an indication and not definitive proof, as the model is sensitive to its own specifications. Third, the environmental Kuznets Curve (EKC) hypothesis has some empirical support. The estimated coefficients show the typical inverted-U relationship, but the tipping point is close to or greater than the actual GDP. It indicates that Saudi Arabia may not be at a stage of transition where economic growth reduces emissions, but this is dependent on the model assumptions and limitations of the data.

Fourth, renewable energy production, including geothermal, shows a positive association with CO₂ emissions in the short run. This finding may reflect the still limited contribution of renewables within a predominantly fossil-fuel-based energy system, as well as potential transitional dynamics. The inclusion of geothermal energy appears to influence the long-run equilibrium relationship; however, the magnitude and direction of this effect should be interpreted cautiously due to measurement and aggregation constraints.

Based on these findings, the policy implications should be viewed as indicative rather than prescriptive. Expanding renewable energy, particularly geothermal and solar, within the framework of Saudi Vision 2030 could contribute to emissions mitigation and support national commitments under the NDCs. In addition, gradual reform of fossil fuel subsidies may improve energy efficiency and influence the growth–emissions relationship. Market-based mechanisms, such as carbon pricing, could also provide incentives for clean energy investment if carefully designed and aligned with economic conditions. Finally, incorporating geothermal energy into long-term energy planning and grid diversification strategies may support the transition toward a more sustainable energy mix.

6. LIMITATIONS

This have a look at has many limitations that must be acknowledged. The assessment is mainly based on aggregated national education records, which may also be difficult to distinguish from regional variations within the growth–emission hyperlink Proxy assigned to geothermal, which may inadequately reflect its true contribution due to limitations in data availability. Third, the sample size, although spanning a long time period, is limited to annual observations, which may affect the robustness of time-series estimations. Fourth, the empirical model does not explicitly incorporate interaction effects (e.g., between GDP and renewable energy), which may be relevant for testing more nuanced hypotheses (such as H₃). Finally, the linear modeling framework may not fully capture potential nonlinearities or asymmetric adjustments in the relationships examined.

Subsequent research could also ameliorate those limitations by using disaggregated regional data, examining nonlinear econometric methods (including NARDL or marginal integration), and evaluating estimates across international locations in the GCC to strengthen the generalizability of effects.

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