Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Analyzing the interactions between economic growth, renewable energy, and human capital in Saudi Arabia

Salma Mohammed Jaghoubi *, Abdullah Abdulmohsen Alfalih

Department of Business Administration, College of Business Administration, Majmaah University, Al-Majmaah 11952, Saudi Arabia

ARTICLE INFO

Article history:
Received 5 February 2025
Received in revised form
18 June 2025
Accepted 28 July 2025

Keywords:
Renewable energy
Economic growth
Human capital
Foreign investment
Energy consumption

ABSTRACT

A nation's economic growth is influenced by several factors, such as natural resources, human capital, technology, and social and political conditions. The interactions among these factors are often complex and not well understood. This study examines the relationship between renewable energy, economic growth, and human capital in Saudi Arabia from 1990 to 2019. Using the Autoregressive Distributed Lag (ARDL) model and Granger causality tests, the research investigates both short-term and long-term connections among these variables. Energy consumption and foreign direct investment (FDI) are included as control variables. The ARDL bounds test confirms a long-term relationship among renewable energy use, economic growth, and human capital. The results show that human capital and FDI have a negative effect on gross domestic product (GDP), suggesting that GDP growth in Saudi Arabia is not closely linked to FDI inflows. In contrast, economic growth positively affects energy consumption. Granger causality tests reveal a one-way short-term causal relationship from FDI and energy use to GDP, and from the Human Capital Index to energy use. A two-way causal relationship is also found between GDP and the Human Capital Index, indicating mutual influence. This study provides new insights into Saudi Arabia's economic transition by connecting traditional growth factors with sustainable development. The findings can help guide policy decisions aimed at promoting long-term growth while supporting environmental sustainability.

1. Introduction

Non-renewable energy resource depletion and the negative impacts of those sources on the environment are among the most critical international challenges today. Nations worldwide have adopted numerous policies to mitigate climate change, promote sustainable economic growth, and adjust living standards (Khurshid et al., 2024). In line with these efforts, Saudi Arabia has released its Vision 2030 initiative, a comprehensive approach aimed at accomplishing sustainability throughout all sectors of the economy. The current research evaluates the complex relationships linking economic growth and human capital with renewable energy use in Saudi Arabia, focusing on the period from 1990 to 2019. Energy critically drives economic development, but its consumption often leads to environmental degradation. While economic activities depend heavily on energy access, increased energy use exacerbates ecological issues such as air pollution, deforestation, and global warming. Consequently, there is a growing need to evaluate the role played by renewable energy in assisting human development and to investigate how human capital can mitigate the negative effects of non-renewable energy by stimulating renewable energy adoption (Rahman et al., 2024).

Recent studies highlight renewable energy's potential to address global warming, emphasizing the importance of replacing fossil fuels with cleaner technologies to reduce CO_2 emissions. Achieving sustainable growth requires the development of eco-friendly energy systems as well as technological innovations, which depend on coordinated efforts by stakeholders. Saudi Arabia, with its vast potential for green energy production, has set a goal of 50% energy generation from renewable sources in 2030, as well as getting to plant ten billion trees, to combat environmental degradation and reduce its reliance on oil. As the world's leading oil producer and one of

* Corresponding Author.
Email Address: s.jaghoubi@mu.edu.sa (S. M. Jaghoubi)
https://doi.org/10.21833/ijaas.2025.08.017
Corresponding author's ORCID profile:
https://orcid.org/0000-0003-3081-3267

the top carbon-emitting nations, Saudi Arabia's commitment to reducing CO_2 emissions by 130 million tons annually by 2030 aligns with its Vision 2030 goals. This study aligns with these objectives by exploring the associations between renewable energy, economic growth, and human capital.

In targeting green growth, societies must use energy more efficiently, decrease carbon emissions, and become less reliant upon conventional energy sources.

Previous studies of the associations which link energy and economic performance are categorized into several groups based on the bivariate associations examined: (i) economic performance and sustainable energy production; (ii) energy usage and economic performance; (iii) sustainable and non-sustainable energy usage and economic performance; (iv) urban environmental sustainability and energy usage; (v) economic performance and human capital; (vi) population growth, energy practices, economic performance, and power surplus; and (vii) economic performance, energy, and human capital.

Additionally, studies have found four main hypotheses regarding the directional links between these variables. The first is the "growth hypothesis," positing that energy use is causally related to economic performance. Second, the "energy conservation hypothesis" suggests that economic development leads to energy consumption. The third, the "feedback hypothesis," proposes a two-way relationship linking energy generation to consumption. Moreover, the "neutrality hypothesis" maintains the non-existence of significance of causality linking economic performance and energy use.

Fig. 1 illustrates the connections linking human capital, sustainable energy, and economic growth. The study investigates these dynamics through the application of autoregressive distributed lag (ARDL) and Granger causality tests, incorporating energy consumption and FDI (foreign direct investment) as control variables. The analysis reveals cointegration linking renewable energy usage, economic growth, and human capital, indicating long-term associations. Additionally, human capital and FDI exhibit notable inhibitory GDP impacts, while energy use generally improves with economic development. FDI is principal to advancing renewable energy technologies, with this factor's effects upon human capital having been a focus in the latest research (An et al., 2023; Ge et al., 2024). Energy represents an essential driver for economic growth, notably for countries that depend economically on oil, as with Saudi Arabia. Energy's role in economic expansion is well-documented, as it reflects both consumption efficiency and economic progress.

The Saudi Vision 2030 focuses on renewable energy investment to diversify the economy, making it essential to analyze the interplay between renewables, economic growth, and human capital. Transitioning from fossil fuels to renewable energy requires rethinking energy use in terms of both quantity and quality. Expanding renewable energy infrastructure promotes sustainable consumption and opens up new economic opportunities, particularly in clean technology sectors. The declining costs of renewable systems enable nations to achieve economic growth with minimal environmental impact. Additionally, reliable and affordable energy is vital for human capital development, as it supports education, research, and skills enhancement.

This study makes various contributions to current literature:

1. The study examines the transition from oil dependence to a renewable energy-driven economy in Saudi Arabia, offering insights into the challenges and opportunities of this shift.
2. It highlights the role of FDI and energy use in shaping Saudi Arabia's renewable energy sector, a key component of Vision 2030.
3. It integrates human capital as mediating the energy-economic growth nexus, demonstrating how skills development influences economic outcomes.
4. It extends the analysis beyond short-term relationships, investigating long-term effects exerted by renewable energy investments upon Saudi Arabia's growth trajectory.
5. It provides a holistic framework that integrates FDI, energy use, and human capital, offering a broad-ranging picture of their interdependencies, as related to Saudi Arabia's energy transition.

This paper continues in several sections: Section 2 offers a literature review, Section 3 provides methodological approaches in the study, and Section 4 discusses the findings, while Section 5 gives the conclusion to the study.

2. Literature review

The literature review considers studies related to economic growth, human capital, and energy consumption, noting that research combining all three variables remains limited. The review begins by examining the relationship between renewable energy and economic growth, followed by findings on human capital and economic growth, and concludes with studies exploring the links between renewable energy and human capital.

2.1. Renewable energy use and economic growth

Studies of the association of renewable energy adoption with economic growth offer conflicting findings. Lin and Moubarak (2014) used ARDL modelling alongside Granger causality tests to analyze China's data from 1977 to 2011, revealing two-way relationships linking renewable energy consumption with economic growth. The findings suggest that economic expansion supports renewable energy development, which in turn fosters further economic growth.

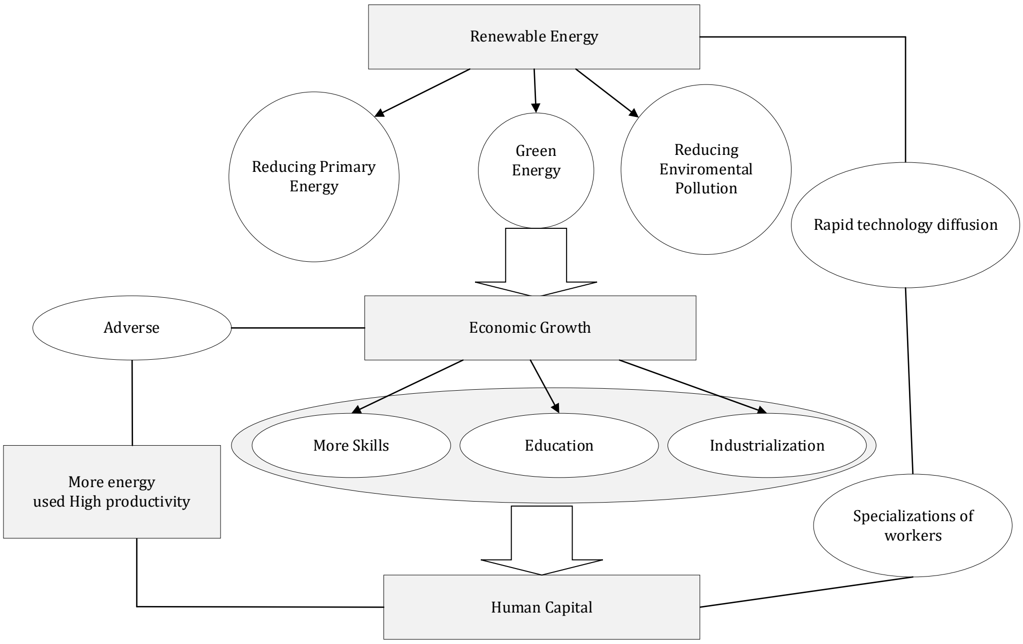

Fig. 1: Relationships linking renewable energy, economic growth, and human

Bhattacharya et al.'s (2016) study of 38 countries with the highest use of renewable energy identified a significant contribution of renewable energy use to economic growth for 57% of the economies examined. Similarly, Inglesi-Lotz (2016) applied the Pedroni cointegration method to 34 OECD countries, identifying that renewable energy use was positively and statistically significantly linked with economic development. Rafindadi and Ozturk (2017) analyzed German data for the period between 1971 and 2013 using Clemente-Montanes-Reyes detrended structural break and Bayer-Hanck combined cointegration testing as well as ARDL bounds tests. The findings indicate that renewable energy positively affects Germany's economy, and that there are two-way relationships linking renewable energy usage with capital and linking capital with economic growth. Khobai et al. (2018) employed ARDL in studying South Africa, finding a long-run association between renewable energy use and economic performance. They also identify a unidirectional causal long-run effect of renewable energy on economic growth, and that in the short term, economic growth positively influences renewable energy use. Ozcan and Ozturk (2019), examining 17 developing countries, found support for the neutrality hypothesis, indicating that energy-saving policy does not harm economic growth in most cases, except for Poland.

Using an ARDL model, Smolović et al. (2020) analyzed the relationships linking renewable energy usage with economic growth across longstanding and more recent EU member states between 2004 and 2018. Their findings indicate a substantial positive long-term impact from renewable energy use upon economic growth, but that short-term impacts are negative and statistically insignificant. Li (2024) underscored the critical function of renewable energy utilization and enhanced energy efficiency in achieving sustainable development, diminishing reliance on fossil fuels, and fostering both economic expansion and environmental protection. Oyegbile et al. (2024) examined the correlation between renewable energy utilization and GDP growth in Sub-Saharan Africa. Their analysis reveals a positive and statistically significant influence of increased renewable energy usage on economic expansion. The study concludes that renewable energy is instrumental in driving economic development, notably by bolstering sustainable infrastructure and alleviating energy scarcity. Liu et al. (2022) showed that solar and wind technology advancements have lowered costs and increased efficiency, boosting economic growth by reducing business energy costs and stimulating innovation. Employing the CS-ARDL model, Majeed et al. (2021) examined the effects of natural resources and economic globalization upon environmental quality. Their analysis demonstrates a significant adverse impact of economic growth and non-renewable energy use on environmental quality, whereas natural resources and renewable energy positively contribute to its improvement. Talha et al. (2021) re-evaluated associations linking energy consumption, increasing GDP, and oil price for Malaysia. Their estimations reveal a positive correlation among these variables from 1986 to 2019. Doytch and Narayan (2021) investigated the impact of service and manufacturing industries on renewable versus non-renewable energy sources, concluding that renewable energy benefits both advanced and developing economies. Konuk et al. (2021) analyzed associations between the use of energy from biomass and economic growth in the NEXT-11 countries (excluding Vietnam) from 1970 to 2017. Their findings reveal a close association linking biomass energy usage to economic growth, with the conservation hypothesis supported for Indonesia, Nigeria, and Bangladesh, while the neutrality hypothesis is validated in Turkey, Egypt, Iran, Korea, Mexico, Pakistan, and the Philippines. Acheampong et al. (2021) investigated the effects of globalization of economies, politics, and society upon energy usage and economic growth for 23 developing countries from 1970 to 2015. Using an IV-GMM estimator, they find a significant positive effect of energy use on economic growth. Zebra et al. (2021) examined renewable energy mini-grids for off-grid electrification in emerging nations, noting that Asian economies outperform African ones in manufacturing and maintaining such systems. They also highlight that lower mini-grid costs increase renewable energy accessibility at the utility level.

Murshed et al. (2022) used STIRPAT modeling to study the relationship between renewables and economic growth in the Argentinian context between 1971 and 2016, revealing a long-term positive association between renewable energy and economic activity.

However, some studies support the neutrality hypothesis, suggesting no significant link between renewable energy consumption and economic growth. Ivanovski et al. (2021) applied the local linear dummy variable estimation (LLDVE) method to OECD and non-OECD economies between 1990 and 2015, finding that non-renewable energy positively impacts economic growth in OECD nations, while renewable energy has negligible effects. Similarly, Islam et al. (2022) found that increased revenue has mixed effects on renewable and non-renewable energy use. Renewable energy usage benefits from institutional quality but is negatively influenced by development processes, which favor non-renewable energy. Ahmad et al. (2020) explored the contribution of renewable energy toward enhancing industrial production in China. Their research reveals that expansion of renewable energy capacity is strongly associated with increased industrial output, particularly in energy-demanding sectors such as steel and cement. The incorporation of renewable energy sources facilitated a reduction in energy costs for manufacturers and ensured more consistent energy availability. Zhao et al. (2022) determined that renewable energy investments enhance energy productivity, enabling economies to produce greater output with reduced energy inputs, and thereby stimulating economic growth. Esposito (2023), using Granger causality testing, explored the contemporary relationship between economic growth and renewable energy for Finland. The analysis revealed a bidirectional, or feedback association linking energy use to future growth rates.

2.2. Human capital and economic growth

While traditional economic growth theory treats labor productivity as an exogenous variable dependent on the labor-to-physical-capital ratio, it overlooks education's function in driving productivity. In the 1980s, novel growth theories emerged, emphasizing innovation and education as key factors supporting human capital for long-term economic growth. Studies exploring the associations between economic growth and human capital have produced varied findings.

Asteriou and Agiomirgianakis (2001) examined the link between education and GDP per capita from 1960 to 1994, finding positive cointegration between the two. Ljungberg and Nilsson (2009) focused on Sweden from 1870 to 2000, applying time-series methods to show that human capital, as assessed through years of schooling, positively influenced economic performance. Tsamadias and Prontzas' (2012) study of Greece from 1960 to 2000, applying Granger's unit root and causality tests, concluded that human capital positively impacts economic growth. Similarly, Pegkas (2014) analyzed Greek data from 1960 to 2009, using error-correction models to reveal long-run relationships between education levels and GDP. They also find unidirectional causality from primary education to growth, bidirectional causality between secondary education and growth, and both long- and short-run causality from higher education on economic growth. Alaali et al. (2015) investigated the effects of human capital (educational and health capital) and energy use upon economic growth in developed and oil-exporting countries. Their results show that educational capital positively influences growth, while health capital has a negative effect. Pelinescu (2015) used an ARDL model to study EU countries from 2000 to 2012, finding that GDP per capita shows a positive link with advanced human capital. Viswanath et al. (2009) applied an aggregate production function to Indian data from 1995 to 1999, demonstrating a strongly positive relation linking human capital with economic growth across 26 states and union territories. Akinwale and Grobler (2019) examined South African data between 1984 and 2015, applying a vector error correction model in identifying long-term relationships linking education, trade openness, and economic growth. Garza-Rodriguez et al. (2020) analyzed Mexico from 1971 to 2010, employing ordinary least squares models to conclude that human capital significantly influences economic development. Hamdan et al. (2020), in studying Saudi Arabia, found no causal effect of higher education investment upon economic growth, while Gheraia et al. (2021) reported a positive effect of education upon Saudi Arabia's economic growth from 1990 to 2017.

2.3. Human capital, energy, and use of renewable energy

Various researchers have empirically investigated relationships between energy resources, renewable energy use, and human capital. For instance, Salim et al. (2017) analyze the variable link between energy use and human capital in China from 1990 to 2010, finding a significant negative relationship, with a 1% rise in human capital reducing energy consumption by 0.18–0.45%.

Shahbaz et al. (2021) investigated the effects of education and export diversification upon US energy demand, using an ARDL model. They identify long-term cointegration among the variables but conclude that education negatively affects energy demand. Yao et al. (2019) studied OECD economies between 1965 and 2014, revealing cross-sectional dependence as well as structural breaks in the relationship that links energy expenditure with human capital. Specifically, a 1% human capital rise decreases total energy use by 15.36%, highlighting human capital's importance to environmental sustainability. Rafindadi and Mika'Ilu (2019) applied ARDL bounds and cointegration tests to the U.K. from 1970 to 2013, examining the effects of renewable energy use on sustainability, capital formation, and economic growth. Their findings confirm significant cointegration among these variables. More recently, Nguyen et al. (2023) explored the role of renewable energy technologies in human development across 77 countries from 2000 to 2019. Using a panel-corrected standard error (PCSE) model, they find a positive relationship between renewable energy consumption and human development, particularly in health, education, and income. Despite the growing body of literature on these topics, significant research gaps remain, especially for Saudi Arabia. While many current works discover the association between renewable energy adoption and economic growth globally, there is limited research examining this dynamic in Saudi Arabia, where the renewables transition is still in its early stages. To support policymakers in attaining Vision 2030 goals, further studies are needed that combine human capital development, energy sector transformation, and economic growth strategies.

3. Data description, econometric methods, and model specification

3.1. Data description

This study advances current understanding by investigating the interplay between human capital, economic development, and renewable energy use in Saudi Arabia. Two control variables, foreign direct investment (FDI) and energy use (EU), are incorporated into the analysis. According to the World Bank in 2022, FDI inflows are pivotal for green energy industries, facilitating capital accumulation and technological innovation. FDI in renewable energy fosters sustainable development by enhancing clean energy expertise and promoting eco-friendly practices. In developing nations, FDI funds renewable energy projects, boosting efficiency and industrial diversification. FDI also strengthens human capital through training and skills development, as demonstrated by An et al. (2023), who noted its role in creating specialized jobs and advancing technical expertise in renewable energy. Ge et al. (2024) further emphasized FDI's contribution to clean technology education and training. Energy, particularly renewable energy, forms a cornerstone for economic growth, especially in oil-dependent economies such as Saudi Arabia. Transitioning to renewables requires rethinking energy use in terms of quantity and quality, as expanding renewable infrastructure supports sustainable consumption and opens up new economic opportunities. Reliable access to energy is essential in developing human capital, improving education, and workforce productivity. Jointly, FDI, renewable energy, and human capital form an integrated strategy for resilient, eco-friendly growth, aligning with global sustainability goals and national initiatives such as Saudi Arabia's Vision 2030. Annual time series data from 1990 to 2019 are used for each variable, selected based on data availability. This research represents one of the first empirical attempts to analyze these interactions within the context of Saudi Arabia's economy over this period. The study focuses on the relationships among five key variables, as outlined in Table 1.

Fig. 2 illustrates the development of GDP, renewable energy (RE), and human capital index (HCI) from 1990-2019.

From Fig. 2, it is seen that these indices are comparable over the period 1990-2019. Indeed, GDP, RE, and HCI moved together during the entire period and followed each other relatively well.

3.2. Econometric methods

The research seeks to assess the relationships linking renewable energy, human capital, and economic growth for Saudi Arabia. To achieve this, various econometric techniques were applied, among which were unit root tests (augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests (Dickey and Fuller, 1979; Phillips and Perron, 1988), ARDL bounds tests, ARDL models, Granger causality testing, and error correction models.

The methodology consists of four key steps:

1. Data transformation: Logarithms are applied to all variables in order to consider issues arising in normal distribution, variance changes, and measurement heterogeneity.
2. Stationarity testing: The application of unit root tests (ADF and PP) identifies variables' order of integration and verifies their stationarity.
3. Cointegration analysis: The ARDL bounds test is applied to identify the existence or otherwise of long-run equilibrium relationships between the human capital index, gross domestic product, and renewable energy. ARDL bounds testing, following Pesaran et al. (1999, 2001), is chosen for its flexibility, as it can handle variables that are stationary at level I(0) or first difference I(1).
4. Causality testing: If cointegration is confirmed, long-run causality is tested to explore the relationships among the variables.

A detailed flowchart outlining the econometric methodology is provided in Fig. 3.

Table 1: Variables examined, with descriptions

Variables	Abbreviations	Official definitions and measurements	Source	Inclusion rationale
Renewable energy consumption	REC	This indicator provides the level of renewable energy as a proportion of total energy usage.	World Bank database	To evaluate the renewable energy sector in Saudi Arabia.
Gross domestic product (in current U.S. dollars)	GDP	The monetary value of services and goods produced within an economy over a certain period. In this research, GDP growth was applied to represent the change or rate of economic performance and output.	World Bank database	To examine the hypothesis that renewable energy usage is affected substantially by economic well-being.
Human capital index	HCI	Index of Human Capital per Person for Saudi Arabia as related to the number of years attending school and returning to education.	Saint Louis's Federal Reserve Bank	To explore the effects of human capital for renewable energy and economic development via schooling and return to education.
Foreign direct investment (as current $ U.S.)	FDI	FDI consists of the total across equity capital, profit reinvestments, and other capital.	Monetary fund and balance of payments database.	To test the "technology transfer" hypothesis.
Energy consumption (kg oil equivalent per capita)	EU	Represents internal production as well as imports and inventory change, deducting exports and fuel supplies for international transport by air and sea. It thus means the use of primary energy before switching to other fuels for end use.	International Energy Agency Statistics	To measure aggregated energy use.

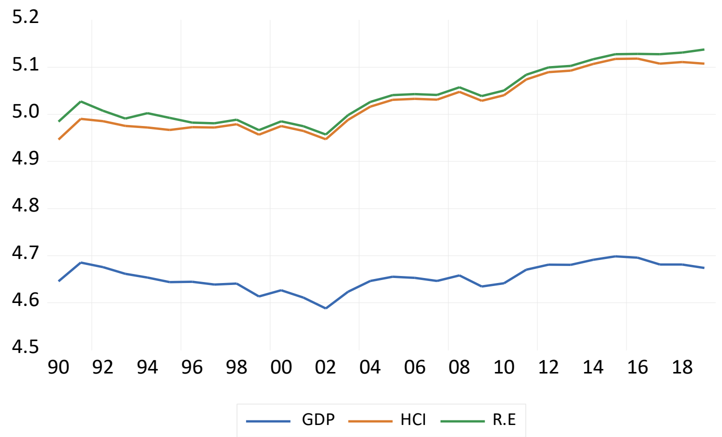

Fig. 2: Dynamics of GDP, HCI, and RE over the period 1990 to 2019

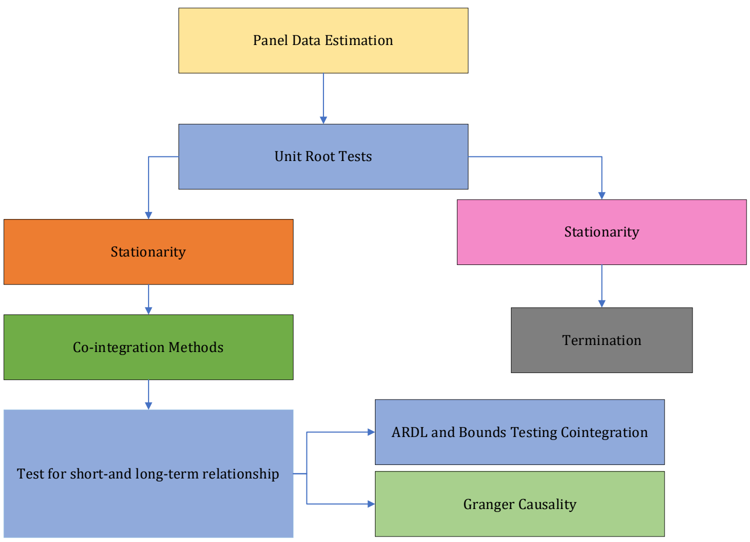

Fig. 3: Flowchart showing econometric methodology

3.3. Model specification

In this study, three equations are estimated:

1. Economic growth equation: Economic growth (GDP) is the dependent variable, with HCI, RE, FDI, and energy use (EU) as independent variables.
2. Renewable energy equation: RE forms the dependent variable, with GDP, HCI, FDI, and EU as independent variables.
3. Human capital equation: HCI forms the dependent variable, with GDP, RE, FDI, and EU as independent variables.

Following the estimation of these equations, the causal relationships among the variables are analyzed using the Granger causality test.

The three ARDL model equations are specified as follows:

- Short run dynamics

$$\mathbf{DLGDP_t} = \alpha_0 + \sum_{i=1}^{p} \gamma_j DLGDP_{t-j} + \sum_{j=0}^{q1} \beta_j\, DLREC_{\,t-j} + \sum_{j=0}^{q2} \delta_j DLHCI_{t-j} + \sum_{j=0}^{q3} \theta_j DLFDI_{t-j} + \sum_{j=0}^{q4} \rho_j DEU_{t-j} + \varphi_0 LGDP_{t-1} + \varphi_1 LREC_{t-1} + \varphi_2 LHCI_{t-1} + \varphi_3 LFDI_{t-1} + \varphi_4 LEU_{t-1} + +\varepsilon_t \quad (1)$$

- Long run dynamics

$$\mathbf{DLREC_t} = \alpha_0 + \sum_{i=1}^{p} \gamma_j DLREC_{t-j} + \sum_{j=0}^{q1} \beta_j DLGDP_{\,t-j} + \sum_{j=0}^{q2} \delta_j DLHCI_{t-j} + \sum_{j=0}^{q3} \theta_j DLFDI_{t-j} + \sum_{j=0}^{q4} \rho_j DLEU_{t-j} + \varphi_0 LREC_{t-1} + \varphi_1 LGDP_{t-1} + \varphi_2 LHCI_{t-1} + \varphi_3 LFDI_{t-1} + \varphi_4 LEU_{t-1} + +\varepsilon_t \quad (2)$$

$$\mathbf{DLHCI_t} = \alpha_0 + \sum_{i=1}^{p} \gamma_j DLHCI_{t-j} + \sum_{j=0}^{q1} \beta_j\, DLGDP_{\,t-j} + \sum_{j=0}^{q2} \delta_j DLREC_{t-j} + \sum_{j=0}^{q3} \theta_j DLFDI_{t-j} + \sum_{j=0}^{q4} \rho_j DLEU_{t-j} + \varphi_0 LHCI_{t-1} + \varphi_1 LGDP_{t-1} + \varphi_2 LREC_{t-1} + \varphi_3 LFDI_{t-1} + \varphi_4 LEU_{t-1} + +\varepsilon_t \quad (3)$$

where, LGDP is the natural logarithm of GDP, as is: LREC for REC; LHCI for HCI; LFDI for FDI; and LEU for EU. α_0 = intercept: p, q1, q2, q3, and q4 are lags and are selected following the Akaike Information Criterion (AIC); ε_t is an error term, and γ_j, β_j, δ_j, θ_j, and ρ_j denote the model's short-run dynamic forces. $\varphi_0, \varphi_1, \varphi_2, \varphi_3$, and φ_4 are employed for the analysis of long-run associations through the bounds cointegration test. Stability, normality, and heteroscedasticity tests are conducted to validate the model estimates. Eqs. 1-3 analyze the nexus between GDP, renewable energy, and human capital in a simultaneous framework. Eq. 1 assesses effects from REC, HCI, and others on GDP. Eq. 2 investigates the impact of GDP, HCI, and other variables on REC. Finally, Eq. 3 analyzes the effect of GDP, REC, and other variables on HCI. The other variables considered in this study are FDI and EU. FDI is considered a vital channel for obtaining advanced green technology and realizing economic growth. Thus, attracting FDI remains necessary for each country's economic growth. Besides this, the EU may significantly affect economic growth, likely decreasing it. Furthermore, numerous studies conclude that an important connection links energy use with HCI. The bounds test is implemented by testing the following hypotheses for each model:

- Null hypothesis (H_0): A long-run connection between GDP, HCI, and REC does not exist. ($\varphi_0 = \varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = 0$)
- Alternative hypothesis (H_1): A long-run connection is identified between GDP, HCI, and REC. ($\varphi_0 \neq 0, \varphi_1 \neq 0, \varphi_2 \neq 0, \varphi_3 \neq 0, \varphi_4 \neq 0$)

Rejection of the null hypothesis indicates the presence of a cointegrating relationship among the variables.

4. Analysis of empirical findings

The findings from the analysis will now be presented, focusing on associations found between GDP, renewable energy use, and the human capital index. First, descriptive statistics are provided, followed by panel unit root test data for both level and first difference across all variables. Finally, results from ARDL modelling and long-run Granger causality testing are discussed.

4.1. Descriptive statistics

Considering the dependent variables, the analysis indicates that LGDP presents a higher mean, with a trend score of 10.7363, while LREC presents a higher standard deviation, with dispersion of 0.4953. Trends for minimum/maximum observation values for LGDP are found to exceed those for LHCI and LREC, at 10.6171 and 10.8188, respectively. LREC's mean trend is -4.7069, as measured based on the proportion of completed end energy use from renewable sources. In comparison, LGDP standard deviation values are far lower than those for LGDP and LHCI. For the control variables, which are LFDI and LEU, descriptive data are given in Table 2.

Fig. 4 provides descriptive statistics across the whole period for all of the selected variables, illustrating trends. The human capital index reveals an increasing trend, indicating significant growth over this period. Concerning renewable energy, peak consumption ran from 1990-1995, with a declining trend from 1996-2016, and then a gradual rise from the beginning of 2017, although not as pronounced as the increase from 1990-1995. Gross domestic product displayed a downward trend during the period from 1991 to 2002, reaching its lowest point during this period. However, from the beginning of 2003, there was a clear increase in GDP, reaching its maximum value in 2015.

4.2. Unit root test analysis

Unit root tests were run to measure stationarity in the dataset. As stated previously, ADF and PP tests were employed in measuring the stationarity of data. The findings of the unit root tests are summarized in Table 3. LGDP, LFDI, and LEU show stationarity at first difference, while LHCI shows stationarity at the level. LREC is stationary across both levels and the first difference. This mixed picture, with I(0) and I(1) series, confirms ARDL's suitability for cointegration analysis.

Table 2: Descriptive statistics

Variables	Observations	Mean	Max	Min	Standard deviation	Skewness	Kurtosis	Jarque-Bera	Probability
LGDP	26	10.7363	10.8188	10.6171	0.0527	-0.2548	2.353	0.6207	0.7331
LHCI	26	0.8746	0.9983	0.6923	0.1003	-0.5765	1.945	2.2374	0.3266
LREC	26	-4.3073	-3.2705	-4.7069	0.4953	1.1552	2.674	4.9912	0.0824
					Control variables				
LFDI	26	22.218	24.398	16.793	1.8684	-1.3295	4.533	8.6366	0.0133
LEU	26	8.6041	8.8017	8.1953	0.1914	-0.5332	2.018	1.9247	0.3819

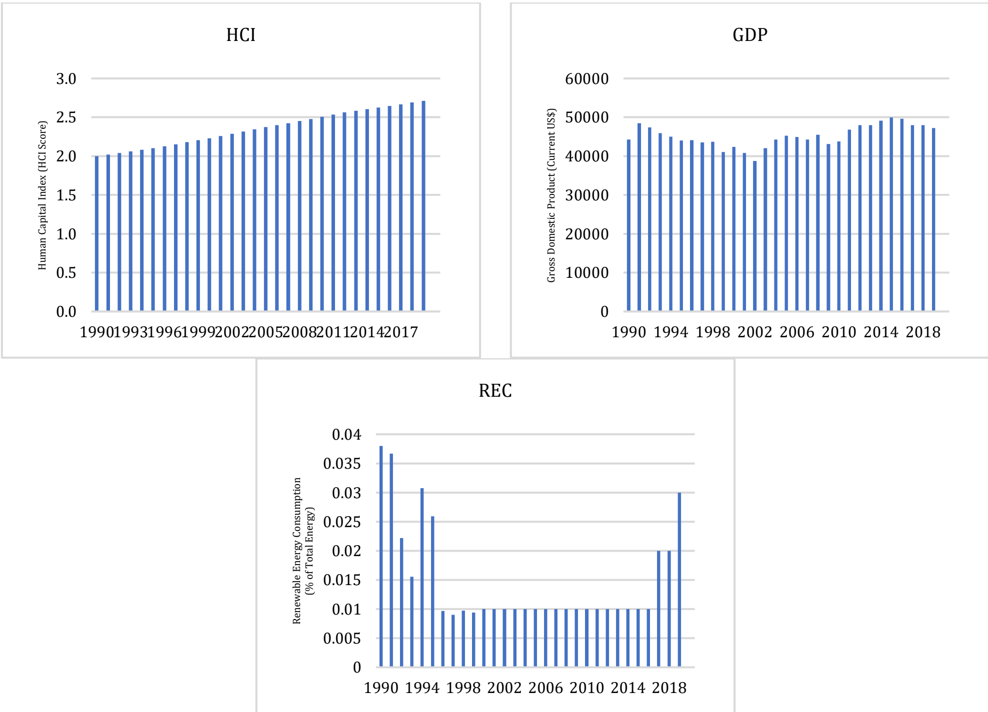

Fig. 4: Trends in GDP, REC, and HCI

Table 3: Unit root test findings

Variable	ADF		PP		Order of integration
	Level	First difference	Level	First difference	
LGDP	-1,5694	-5,7090***	-1,6395	-5,6771***	I(1)
LHCI	-4,2513***	-1,9339	0,0437	-1,9796	I(0)
LREC	-3,1742**	-5,5368***	-2.7035**	-4,5894***	I(0)
LFDI	-2,1140	-3,2954**	-1,6493	-3,3108**	I(1)
LEU	-0,6634	-10,2942***	-1,1568	-10,0557***	I(1)

***, **: Respective 1% and 5% significance levels

4.3. Bounds test and long-run analyses

With reference to the Akaike information criteria for selection of optimum modelling lag, lag 4 was found to be optimal. An ARDL model was run three times: In the first case, with LGDP as a dependent variable, to measure linkages associated among economic development, renewable energy use, and human capital; while the second and third cases considered renewable energy and human capital, respectively, as dependent variables and evaluated their effects upon economic growth. The bounds test for cointegration findings can be viewed in Table 4.

From Table 4 above, estimated F-values (7.1029, 10.485, and 4.3664) for the three ARDL models exceed the upper critical value (4.37), regardless of significance levels (10%, 5% and 2.5%). Thus, this leads to rejection of the null hypothesis, which declares that cointegration is absent, and consequently, a stable long-run association between GDP, REC, human capital, FDI, and energy use is confirmed for the Saudi context, which presents the opportunity to estimate long-term effects between variables.

Table 5 presents associations linking each variable in terms of significance and direction.

Table 4: ARDL bounds test

Test statistic	Value	K
	F-statistic	
ARDL (LGDP dependent variable)	7.1029	4
ARDL (LREC dependent variable)	10.485	4
ARDL (LHCI dependent variable)	4.3664	4
	Critical value bounds	
Significance	**I0 bound**	**I1 bound**
10%	2.2	3.09
5%	2.56	3.49
2.5%	2.88	3.87
1%	3.29	4.37

Table 5: ARDL models and long run estimates

Variable	Coefficient	Standard error	T-statistic	Probability
MODEL 1 (Dependent variable = GDP)				
LHCI	-2.776511	0.814537	-3.408698	0.0078
LREC	-0.042826	0.032053	-1.336096	0.2143
LEU	2.219995	0.614048	3.615342	0.0056
LFDI	-4.71E-12	2.27E-12	-2.075727	0.0677
C	-6.508711	4.814206	-1.351980	0.2094
$LEC = LGDP - (-2.7765\,LHCI - 0.428\,LREC + 2.2200\,LEU - 4.71E^{-12}LFDI - 6.5087)$ (4)				
Model 2 (Dependent variable = REC)				
LHCI	-75.42080	56.48047	-1.335343	0.2740
LGDP	0.313566	7.142421	0.043902	0.9677
LFDI	-6.14E-11	6.78E-11	-0.905667	0.4319
LEU	44.69260	35.31314	1.265608	0.2950
C	-333.8081	292.2826	-1.142073	0.3363
$LEC = LREC - (0.3136\,LGDP - 75.4208\,LHCI - 0.0000\,LFDI + 44.6926\,LEU - 333.8081$ (5)				
Model 3 (Dependent variable = HCI)				
LGDP	0.281877	0.275318	1.023821	0.4136
LREC	-0.020463	0.012880	-1.588775	0.2531
LFDI	-1.42E-12	6.85E-13	-2.081369	0.1729
LEU	0.649682	0.050304	12.91508	0.0059
C	-8.068831	3.266493	-2.470181	0.1322
$EC = LHCI - (0.2819\,LGDP - 0.0205\,LREC - 0.0000LFDI + 0.6497\,LEU - 8.0688)$ (6)				

Considering Eq. 4 in Table 5 above, it is seen that FDI and human capital in Saudi Arabia have significant negative impacts on gross domestic product, implying that a 1% human capital and FDI would reduce GDP by 2.7765 and -4.71E-12, respectively.

These findings present significant challenges for Saudi Vision 2030, which identifies HCI and FDI as critical factors driving economic diversification and sustainable growth. The adverse effects of HC and FDI upon economic growth are inconsistent with Vision 2030's goals. These results align with earlier findings by Belloumi and Alshehry (2018), who observed a similar negative relation of FDI with Saudi economic growth from 1970 to 2015.

The negative relationship between HCI and GDP highlights a potential failure in matching skills being developed with the economy's requirements. To address this, policymakers should reform education and training systems to align with the demands of emerging sectors such as renewable energy, technology, and advanced manufacturing. Emphasizing STEM (science, technology, engineering, and mathematics) education and fostering innovation-driven skills will be critical to achieving Vision 2030's objectives. Similarly, the adverse impact of FDI underscores the need for more strategic investment policies. Saudi Arabia should prioritize attracting FDI in sectors aligned with Vision 2030, such as renewable energy, tourism, and healthcare. Additionally, policies should ensure that FDI contributes to knowledge transfer, job creation, and the development of local supply chains. In contrast, energy use significantly positively affects long-run GDP. The findings indicate that when energy use rises by 1%, a 2.22% rise in GDP occurs. This underscores energy's critical role in driving economic development, as economic growth inherently demands higher energy consumption. As Saudi Arabia's economy expands, its population naturally consumes more energy, aligning with theoretical expectations. These results are consistent with earlier studies, such as those by Akinwale (2018).

Given that Saudi Arabia is strongly economically dependent upon oil production and related services, with GDP growth still closely tied to oil revenues, these findings are not surprising. However, this reliance on energy-intensive sectors presents both opportunities and challenges for Saudi Vision 2030, with its aims of economic diversification and promotion of sustainable development.

Considering Eq. 5, human capital and FDI have a negative impact on renewable energy usage, and GDP and energy use positively impact REC. It is also observed that none of the variables significantly affect renewable energy, with insignificant effects confirmed from all of the variables used on long-run REC. The positive but not significant effect of GDP and EU on REC, as revealed in this study, has similarities with the outcomes provided by researchers in previous case studies (Ankrah and Lin, 2020; Anton and Nucu, 2020). Energy consumption's positive association with REC reflects the growing demand for energy as the economy develops. To meet this demand sustainably, Saudi Arabia is likely investing in renewable energy as a complementary source to traditional energy, ensuring a balanced and diversified energy mix. In addition, GDP's positive association with REC implies that economic growth provides access to the finance and technology required to invest in renewable energy infrastructure. As the economy expands, governments and private sectors are better positioned to fund and adopt renewable energy solutions, aligning with global sustainability trends.

FDI exhibits a negative but not significant influence on REC in Saudi Arabia, implying that an increase in FDI does not significantly decrease REC in the country. The study's findings of a negative relationship between FDI and REC could indicate that foreign investments are not being directed toward renewable energy projects. Instead, FDI may be concentrated in traditional sectors such as oil and gas, which remain dominant in Saudi Arabia's economy. Thus, FDI did not represent a significant channel for transferring resources, technology, skills, and expertise into the state's economy. Potentially, FDI could boost business-to-business investment and lead to technological innovation, which would reduce reliance on renewable energy while boosting energy efficiency. Based on Eq. 6, only energy usage demonstrates significant positive impacts upon human capital, and these findings imply that increasing energy consumption by 1 % would facilitate a 0.6496 % increase in human capital. This result supports the growth hypothesis, indicating that energy consumption forms a key driver of economic growth and human capital development. According to this hypothesis, energy is treated as a direct factor of production, alongside capital and labor, essential for sustaining and enhancing economic and social progress. The econometric tests conducted in this study consistently reveal statistically significant relationships between the models' variables. This leads to rejection of the null hypothesis and acceptance of the alternative hypothesis. This supports a long-run connection linking GDP, human capital index, and renewable energy consumption.

4.4. Short-run relationships and error correction modelling analysis

Tables 6, 7, and 8 present findings from error correction models (ECMs) and short-run relationships. The adjustment coefficient is statistically significant only for the first ARDL model in Table 6, where it is negative and falls within the range of 0 to 1 in absolute value. At 1% significance, it differs from 0 by a significant amount, confirming the presence of an error correction mechanism in the short-run relationship (-0.75188, p=0.0000). The negative sign shows that correction of deviations from long-run equilibrium occurs at a 75.188% rate annually, suggesting a relatively fast adjustment process.

In contrast, the other two ARDL models (Tables 7 and 8) show positive adjustment coefficients (0.46 and 0.09) for renewable energy usage and the human capital index as dependent variables, respectively. This suggests potential multicollinearity issues in these models.

Table 6: Case for LGDP as a dependent variable

ARDL				
Variable	Coefficient	Standard error	T-statistic	Probability
CointEq(-1)*	-0.751888	0.092345	-8.142122	0.0000***

***, *: Respective 1% and 10% significance

Table 7: Case for LREC as a dependent variable

ARDL				
Variable	Coefficient	Standard error	T-statistic	Probability
CointEq(-1)*	0.460045	0.035518	12.95260	0.0010***

***, *: Respective 1% and 10% significance

Table 8: Case for LREC as a dependent variable

ARDL				
Variable	Coefficient	Standard error	T-statistic	Probability
CointEq(-1)*	0.093146	0.009727	9.575722	0.0107**

**, *: Respective 5% and 10% significance

After selecting the long-term model, the VECM model can be assessed. The appropriate lag length for the ARDL model is then selected. It is critical to identify a suitable lag length in relation to each foundational variable within the ARDL model to ensure that Gaussian error terms are achieved (meaning standard normal error terms without issues such as non-normality, autocorrelation, or heteroscedasticity). For model selection for the long-run underlying equation, the optimum lag length(k) must be identified with appropriate model order selection criteria, e.g., the Akaike Information Criterion (AIC). From Fig. 5, ARDL (1, 4, 1, 2, 4) is shown to give the optimum VECM lag length.

The co-integration analysis examines the short-run associations between variables. Key findings in Table 9 include that the lagged values of LHCI show mixed effects. While most coefficients are not statistically significant, the third lag (LHCI(-3)) has a significant positive impact. This suggests that past improvements in human capital (three periods prior) positively influence current economic conditions in the short run. The coefficient for LREC is negative and insignificant, indicating no significant short-run effect of renewable energy use on the model. The first lag of LEU (LEU(-1)) has a significant negative impact, suggesting that past energy use negatively affects current economic conditions in the short run. This could reflect inefficiencies or over-reliance on energy-intensive sectors.

FDI shows significant short-run positive effects, particularly in the first and third lags. This indicates that past FDI inflows positively influence current economic performance, likely through knowledge transfer, job creation, or infrastructure development.

The error correction term in Table 9 shows strong significance, which confirms that there is a long-run equilibrium association among variables. A negative sign demonstrates that corrections of deviations from the long-run equilibrium occur at a rate of 75.188% annually, suggesting a relatively fast adjustment process.

Concerning the long-run coefficients, the results in Table 9 indicate that, during the sample period, HC's coefficient is negative and significant, indicating that human capital negatively impacts GDP in the long run. This suggests that skills being developed to meet the economy's requirements are not aligned, potentially due to inadequate alignment of education and training programs with economic demands. Similarly, the FDI is negative with marginal significance, suggesting a slight negative long-run impact of FDI on GDP. This could be due to FDI being concentrated in non-productive sectors or insufficient integration into the local economy. In addition, the insignificant negative coefficient of REC suggests that renewable energy consumption does not significantly influence GDP over the long run, which may reflect the limited place of renewables within Saudi Arabia's energy mix during the study period.

However, energy use strongly positively influences long-run GDP. This aligns with Saudi Arabia's reliance on energy-intensive sectors, particularly oil and gas, to drive economic growth.

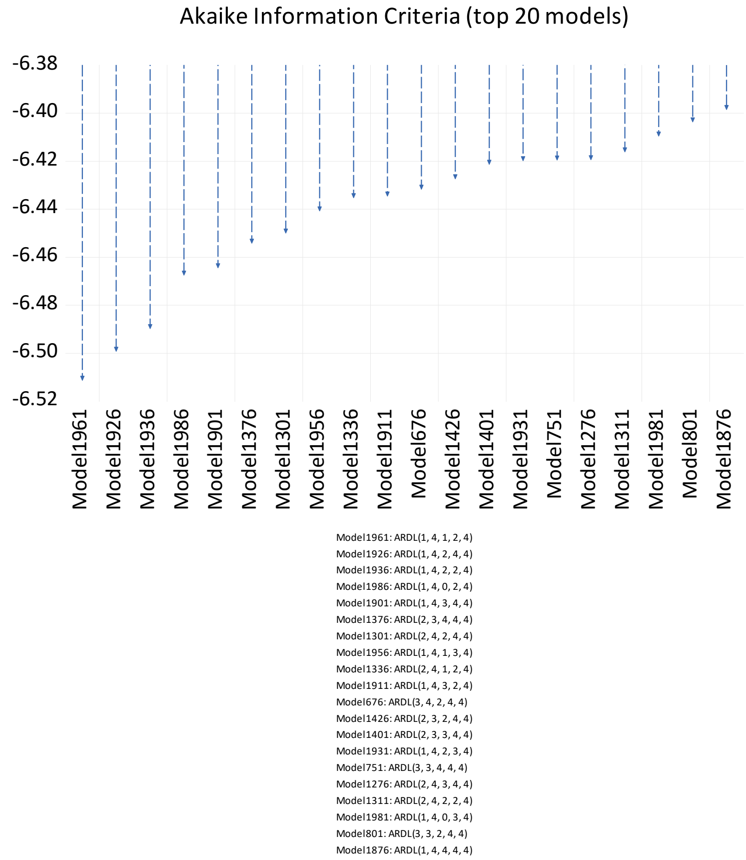

Fig. 5: Appropriate ARDL model based on AIC criteria

Table 9: ARDL co-integration and long-run forms

Selected model: ARDL (1, 4, 1, 2, 4)				
Co-integrating form				
Variable	Coefficient	Standard error	T-statistic	Probability
D(LHCI)	-3.753014	5.191342	-0.722937	0.4881
D(LHCI(-1))	3.343004	7.102937	0.470651	0.6491
D(LHCI(-2))	12.90686	7.104479	1.816722	0.1026
D(LHCI(-3))	17.39093	6.163594	2.821557	0.0200
D(LREC)	-0.009865	0.011414	-0.864228	0.4099
D(LEU)	0.127373	0.134704	0.945573	0.3691
D(LEU(-1))	-0.842571	0.198090	-4.253477	0.0021
D(LFDI)	1.28E-12	6.85E-13	1.875347	0.0935
D(LFDI(-1))	1.88E-12	9.84E-13	1.910565	0.0884
D(LFDI(-2))	9.95E-13	8.49E-13	1.170876	0.2717
D(LFDI(-3))	3.42E-12	7.11E-13	4.814249	0.0010
CointEq(-1)	-0.75188	0.092345	-8.142122	0.0000
Long-run coefficients				
LHCI	-2.776511	0.814537	-3.408698	0.0078
LREC	-0.042826	0.032053	-1.336096	0.2143
LEU	2.219995	0.614048	3.615342	0.0056
LFDI	-4.71E-12	2.27E-12	-2.075727	0.0677
C	-6.508711	4.814206	-1.351980	0.2094

4.5. Post-estimation diagnostic tests

In this step, the objective is an assessment of validity for the estimated ARDL bounds test model through diagnostic testing, as follows: The Jarque-Bera test, assessing normal distribution; the Breusch-Godfrey Serial Correlation LM test; the Breusch-Pagan-Godfrey, ARCH, and Grejser tests for heteroscedasticity; and the Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ), testing model stability. Only the first ARDL model is considered, wherein GDP is a dependent variable. It is concluded from Table 10 that all of the probabilities are greater than 0.05, which suggests that the findings are robust. Estimated optimal ARDL residuals do not support serial correlation in the various lags considered. Therefore, as there is no error autocorrelation, this suggests that all significant information is accounted for by the reduced model, with the estimated ARDL model being considered well-fitted. Moreover, regarding heteroscedasticity tests, rejection of the null hypothesis (H0: Absence of heteroscedasticity) cannot take place, and heteroscedasticity is not found in the ARDL model's residuals. Therefore, residual variance is constant. Also, the Jarque-Berra test shows normal distribution of residuals, as the Jarque-Bera probability is greater than 5%. Additionally, the CUSUM and CUSUMSQ tests (Fig. 6) present plots of the CUSUM and the CUSUMSQ, which fall inside the 5% range of significance within the two straight edges, implying stability of the association between the variables during the sampled range of time. Overall, findings from the various diagnostic test types lead to validation of the ARDL model (1, 4, 1, 2, 4) in statistical terms. Moreover, since the absolute value of the t-statistic (5.482641) for the t-bound Test exceeds the absolute values of the upper limit critical values at the 10% level, it is concluded that this relationship is logical (Table 11). On the other hand, after estimating the model with error correction, the absolute value of the t-statistic of the error correction term (ECT) improves (7.249293) and becomes significant at the 1%, 2.5%, 5% and 10% level (Table 12). This therefore gives adequate justification to continue and estimate long- and short-term relationships using the ARDL cointegration model.

Table 10: Diagnostic testing outcomes

Item	Applied test	F-statistic	Probability	Decision
Serial correlation	Breusch-Godfrey serial correlation LM	2,642406	0.1576	No serial correlation
Heteroscedasticity	Breusch-Pagan-Godfrey	1.150429	0.4302	No heteroscedasticity
	ARCH	0.019158	0.8911	
	Glejser	1.777537	0.1920	
Normality	Jarque-Berra	0.157126	0.9244	Variables are normally distributed

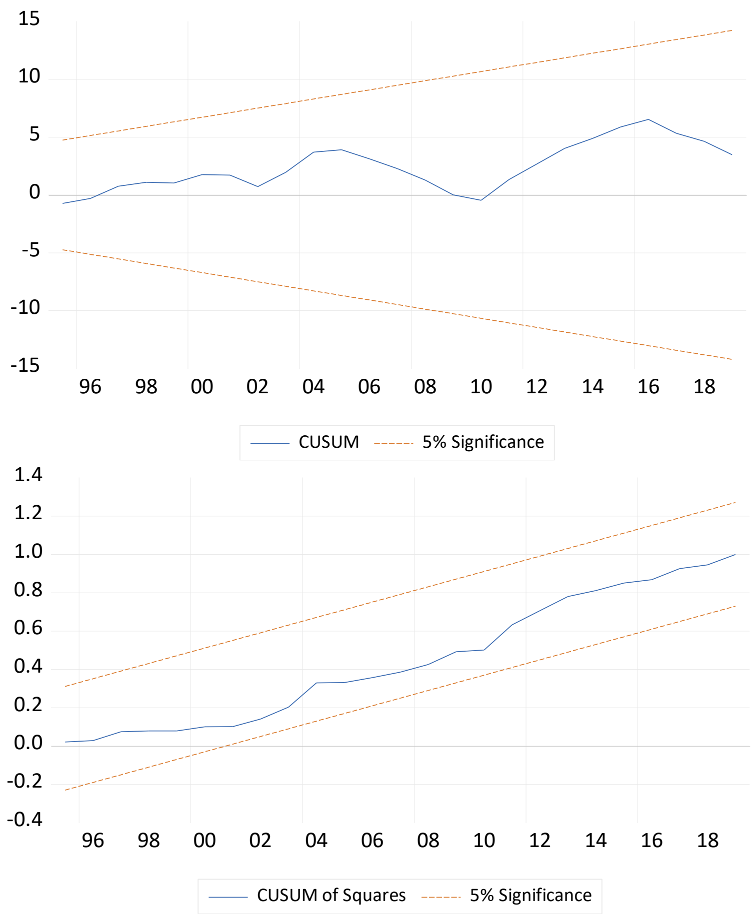

Fig. 6: Cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) at 5% significance; Y-axis is Cumulative Sum

Table 11: t-bound test findings for ARDL long-run form and bounds test

T-bounds test		Null hypothesis: No level relationship		
Test statistic	Value	Significance	I(0)	I(1)
T-statistic	-5.482641	10%	-1.62	-3.26
		5%	-1.95	-3.6
		2.5%	-2.24	-3.89
		1%	-2.58	-4.23

Table 12: t-bound test for ARDL error correction regression

T-bounds test		Null hypothesis: No level relationship		
Test statistic	Value	Significance	I(0)	I(1)
T-statistic	-7.249293	10%	-1.62	-3.26
		5%	-1.95	-3.6
		2.5%	-2.24	-3.89
		1%	-2.58	-4.23

To identify misspecification in a regression model, and particularly to identify how far the dependent variable can be explained using non-linear combinations of fitted values, the Ramsey RESET (Regression Specification Error Test) was used. This test provides a t-statistic, an F-statistic, and corresponding p-values. The null hypothesis (H0) implies that the model does not have omitted variables, and is correctly specified, while the alternative hypothesis (H1) denotes that the model has omitted variables and is mis-specified. Table 13 summarizes the Ramsey Reset test findings. All probabilities exceed 0.05, meaning that the null hypothesis is accepted, revealing that the model is correctly specified.

4.6. Granger causality test analysis

Table 14 presents empirical findings from pairwise Granger causality tests, revealing short-run causal relationships among key variables in Saudi Arabia's economy. The findings point to a unidirectional causal connection linking FDI and EU to GDP, as well as from HCI to EU. The relationship between HCI and GDP is bidirectional, with rejection of the null hypothesis that human capital does not Granger-cause GDP at 10% significance. The null hypothesis that GDP does not Granger-cause human capital is rejected at 1% significance. This two-way relationship aligns with the theory that a skilled workforce drives economic growth, while economic growth fosters investments in education and training. These findings are consistent with studies by Bokhari (2017) and Gheraia et al. (2021), but contrast with those of Hamdan et al. (2020), who found no causal effect of human capital on economic development. Based on the sample period, no significant causal relationships were found between REC and other variables (GDP, HCI, FDI, or EU), suggesting that renewable energy adoption in Saudi Arabia has not yet reached a level where it significantly influences or is influenced by economic growth, human capital, or energy use. This reflects the early stages in renewable energy integration within Saudi Arabia's energy mix, despite ongoing efforts to implement renewable energy technologies. The country's economy continues to depend significantly on fossil fuels for rapid growth. Additionally, rejection of the null hypothesis that FDI does not Granger-cause GDP at 5% significance supports the idea that FDI drives economic growth by creating jobs, via technology transfers, and due to developing infrastructure. However, no significant causal relationships were found between FDI and other variables (HCI, REC, or EU), suggesting that FDI inflows are primarily directed toward sectors that directly impact GDP rather than human capital or renewable energy. These findings highlight the importance of prioritizing human capital development, attracting strategic FDI, and promoting energy efficiency to support Saudi Arabia's Vision 2030 goals. While renewable energy does not yet show significant causal links, its role is expected to grow as the country transitions toward a more sustainable energy mix.

Table 13: Ramsey reset test results

	Value	df	Probability
T-statistic	0.154499	7	0.8816
F-statistic	0.023870	(1, 7)	0.8816
Likelihood ratio	0.088509	1	0.7661

Table 14: Pairwise Granger causality tests

Null hypothesis	F-statistic
LHCI does not Granger Cause LGDP	3.36636*
LGDP does not Granger Cause LHCI	9.53741***
LREC does not Granger Cause LGDP	0.43086
LGDP does not Granger Cause LREC	2.20709
FDI does not Granger Cause LGDP	3.91050**
LGDP does not Granger Cause FDI	0.09289
LREC does not Granger Cause LHCI	0.13766
LHCI does not Granger Cause LREC	1.48436
FDI does not Granger Cause LHCI	0.11720
LHCI does not Granger Cause FDI	0.60207
LEU does not Granger Cause LHCI	1.63515
LHCI does not Granger Cause LEU	3.98842**
FDI does not Granger Cause LREC	0.12828
LREC does not Granger Cause FDI	0.07663
LEU does not Granger Cause LREC	1.12049
LREC does not Granger Cause LEU	0.40164
LEU does not Granger Cause FDI	0.21379
FDI does not Granger Cause LEU	1.78342
LEU does not Granger Cause LGDP	3.78398**
LGDP does not Granger Cause LEU	0.68827

***, **, *: Respective 1%, 5% and 10% significance levels

5. Conclusion

This study examines the relationships between Saudi Arabia's renewable energy use, human capital, and economic growth from 1990 to 2019, with foreign direct investment and energy consumption included as control variables. The topic is timely and relevant, given the limited research on these variables in the Saudi context and the government's ongoing economic transformation under Vision 2030. The ARDL bounds method is applied, as it is suitable for models with mixed I(0) and I(1) variables. The results show cointegration among renewable energy use, economic growth, and human capital, indicating the presence of long-run relationships. The analysis finds that FDI has a significant negative effect on GDP, suggesting that higher GDP is associated with lower FDI inflows. This implies that economic growth in Saudi Arabia is not strongly supported by foreign investment, possibly due to the dominance of oil revenues and the limited diversification of sectors that attract FDI. HCI also has a significant negative effect on GDP, indicating a mismatch between developed skills and the needs of the economy. This underlines the need for reforms in education and training to align human capital development with the requirements of emerging sectors. Energy consumption has a significant positive effect on GDP, reflecting the reliance on energy-intensive sectors. However, REC is not a significant driver of economic growth, likely due to the economy's dependence on oil and the early stage of renewable energy adoption. Granger causality tests show one-way causal links from FDI and EU to GDP, and from HCI to EU, as well as a two-way relationship between GDP and HCI. These results suggest that Saudi Arabia should prioritize the development of human capital, attract strategic FDI, and promote energy efficiency and diversification. Although renewable energy currently has no significant effect on GDP, its importance is expected to increase as the country transitions to a more sustainable energy mix under Vision 2030. Policymakers should aim to align education with the needs of emerging sectors, encourage FDI in renewable energy and tourism, and accelerate renewable energy investments to support long-term economic diversification, sustainability, and quality of life. This study has some limitations. First, linear interpolation and extrapolation were used to address missing data, which, while not affecting long-run relationships, may cause size distortion. Second, the analysis focuses only on Saudi Arabia; future research could extend to the GCC region to offer broader insights into how human capital, renewable energy, and economic performance influence environmental quality and economic diversification.

6. Further discussion

Based on the foregoing analysis, several policy recommendations are proposed. In alignment with Saudi Arabia's Vision 2030 goals, the government should prioritize human capital development by investing in vocational education alongside traditional education providers such as schools, colleges, and universities. This approach would ensure that the workforce meets the specific needs of key industries. Additionally, the government should incentivize organizations to develop their human resources by providing adequate financial support and resources. It is also crucial to integrate more field and practical training opportunities into formal education programs, allowing the student to obtain active experience and transition from the academic to the industrial context.

Furthermore, the study highlights the need for Saudi Arabia to attract greater foreign direct investment by exploring innovative strategies and creating positive spillover channels to foster FDI inflows. This would not only enhance economic growth but also facilitate technology transfer and skill development.

Lastly, the study recommends that the Saudi government fully leverage alternative and renewable energy resources, including wind and solar energy generation, to drive green economic growth as well as improve the quality of the environment. These measures would align with global sustainability goals and support the nation's transition toward a more diversified and resilient economy.

List of abbreviations

ADF	Augmented dickey-fuller
AIC	Akaike information criterion
ARCH	Autoregressive conditional heteroskedasticity
ARDL	Autoregressive distributed lag
C	Constant
CO_2	Carbon dioxide
CS-ARDL	Cross-sectional autoregressive distributed lag
CUSUM	Cumulative sum
CUSUMSQ	Cumulative sum of squares
df	Degree of freedom
ECT	error correction term
EU	Energy consumption
FDI	Foreign direct investment
GCC	Gulf Cooperation Council
GDP	Gross domestic product
GMM	Generalized method of moments
HCI	Human capital index
IV–GMM	Instrumental variables – generalized method of moments
IV	Instrumental variable
K	Number of regressors
LM	Lagrange multiplier
LLDVE	Local linear dummy variable estimation
LEU	Natural logarithm of EU
LFDI	Natural logarithm of FDI
LGDP	Natural logarithm of GDP
LHCI	Natural logarithm of HCI
LREC	Natural logarithm of REC
OECD	Organisation for economic co-operation and development
PCSE	Panel-corrected standard error
PP	Phillips-Perron
REC	Renewable energy consumption

RESET	Regression specification error test
STEM	Science, technology, engineering, and mathematics
STIRPAT	Stochastic impacts by regression on population, affluence, and technology
VECM	Vector error correction model

Acknowledgment

The authors extend their appreciation to the Deanship of Postgraduate Studies and Scientific Research at Majmaah University for funding this research work through project number R-2025-1699.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Acheampong AO, Boateng E, Amponsah M, and Dzator J (2021). Revisiting the economic growth–energy consumption nexus: Does globalization matter? Energy Economics, 102: 105472. https://doi.org/10.1016/j.eneco.2021.105472

Ahmad T, Huanxin C, Zhang D, and Zhang H (2020). Smart energy forecasting strategy with four machine learning models for climate-sensitive and non-climate sensitive conditions. Energy, 198: 117283. https://doi.org/10.1016/j.energy.2020.117283

Akinwale YO (2018). An empirical analysis of short run and long run relationships between energy consumption, technology innovation and economic growth in Saudi Arabia. International Journal of Energy Economics and Policy, 8(4): 139-146.

Akinwale YO and Grobler WC (2019). Education, openness and economic growth in South Africa: Empirical evidence from VECM analysis. The Journal of Developing Areas, 53(1): 51-64. https://doi.org/10.1353/jda.2019.0003

Alaali F, Roberts J, and Taylor K (2015). The effect of energy consumption and human capital on economic growth: An exploration of oil exporting and developed countries. Sheffield Economics Research Papers Series No. 2015015, University of Sheffield, Sheffield, UK.

An NB, Kuo YL, Mabrouk F, Sanyal S, Muda I, Hishan SS, and Abdulrehman N (2023). Ecological innovation for environmental sustainability and human capital development: The role of environmental regulations and renewable energy in advanced economies. Economic Research-Ekonomska istraživanja, 36(1): 243-263. https://doi.org/10.1080/1331677X.2022.2120046

Ankrah I and Lin B (2020). Renewable energy development in Ghana: Beyond potentials and commitment. Energy, 198: 117356. https://doi.org/10.1016/j.energy.2020.117356

Anton SG and Nucu AEA (2020). The effect of financial development on renewable energy consumption: A panel data approach. Renewable Energy, 147: 330-338. https://doi.org/10.1016/j.renene.2019.09.005

Asteriou D and Agiomirgianakis GM (2001). Human capital and economic growth: Time series evidence from Greece. Journal of Policy Modeling, 23(5): 481-489. https://doi.org/10.1016/S0161-8938(01)00054-0

Belloumi M and Alshehry A (2018). The impacts of domestic and foreign direct investments on economic growth in Saudi Arabia. Economies, 6(1): 18. https://doi.org/10.3390/economies6010018

Bhattacharya M, Paramati SR, Ozturk I, and Bhattacharya S (2016). The effect of renewable energy consumption on economic growth: Evidence from top 38 countries. Applied Energy, 162: 733-741. https://doi.org/10.1016/j.apenergy.2015.10.104

Bokhari AA (2017). Human capital investment and economic growth in Saudi Arabia: Error correction model. International Journal of Economics and Financial Issues, 7(4): 104-112.

Dickey DA and Fuller WA (1979). Distribution of the estimators for autoregressive time series with a unit root. Journal of the American Statistical Association, 74(366a): 427-431. https://doi.org/10.1080/01621459.1979.10482531

Doytch N and Narayan S (2021). Does transitioning towards renewable energy accelerate economic growth? An analysis of sectoral growth for a dynamic panel of countries. Energy, 235: 121290. https://doi.org/10.1016/j.energy.2021.121290

Esposito L (2023). Renewable energy consumption and per capita income: An empirical analysis in Finland. Renewable Energy, 209: 558-568. https://doi.org/10.1016/j.renene.2023.03.139

Garza-Rodriguez J, Almeida-Velasco N, Gonzalez-Morales S, and Leal-Ornelas AP (2020). The impact of human capital on economic growth: The case of Mexico. Journal of the Knowledge Economy, 11: 660-675. https://doi.org/10.1007/s13132-018-0564-7

Ge L, Zheng H, Wang C, Ye Y, and Xu Z (2024). The impact of foreign direct investment on green technology innovation: Evidence from the threshold effect of absorptive capacity. Journal of Urban Technology, 31(3): 107-130. https://doi.org/10.1080/10630732.2024.2385116

Gheraia Z, Benmeriem M, Abdelli HA, and Saadaoui S (2021). The effect of education expenditure on economic growth: The case of the Kingdom of Saudi Arabia. Humanities and Social Sciences Letters, 9(1): 14-23. https://doi.org/10.18488/journal.73.2021.91.14.23

Hamdan A, Sarea A, Khamis R, and Anasweh M (2020). A causality analysis of the link between higher education and economic development: Empirical evidence. Heliyon, 6(6): e04046. https://doi.org/10.1016/j.heliyon.2020.e04046 **PMid:32529066 PMCid:PMC7276432**

Inglesi-Lotz R (2016). The impact of renewable energy consumption to economic growth: A panel data application. Energy Economics, 53: 58-63. https://doi.org/10.1016/j.eneco.2015.01.003

Islam MM, Irfan M, Shahbaz M, and Vo XV (2022). Renewable and non-renewable energy consumption in Bangladesh: The relative influencing profiles of economic factors, urbanization, physical infrastructure and institutional quality. Renewable Energy, 184: 1130-1149. https://doi.org/10.1016/j.renene.2021.12.020

Ivanovski K, Hailemariam A, and Smyth R (2021). The effect of renewable and non-renewable energy consumption on economic growth: Non-parametric evidence. Journal of Cleaner Production, 286: 124956. https://doi.org/10.1016/j.jclepro.2020.124956

Khobai H, Kolisi N, and Moyo C (2018). The relationship between trade openness and economic growth: The case of Ghana and Nigeria. International Journal of Economics and Financial Issues, 8(1): 77-82.

Khurshid N, Egbe CE, and Akram N (2024). Integrating non-renewable energy consumption, geopolitical risks, economic development with the ecological intensity of wellbeing: Evidence from quantile regression analysis. Frontiers in Energy Research, 12: 1391953. https://doi.org/10.3389/fenrg.2024.1391953

Konuk F, Zeren F, Akpınar S, and Yıldız Ş (2021). Biomass energy consumption and economic growth: Further evidence from NEXT-11 countries. Energy Reports, 7: 4825-4832. https://doi.org/10.1016/j.egyr.2021.07.070

Li D (2024). Green finance, fossil fuel efficiency, and sustainable development in OECD. Resources Policy, 98: 105306. https://doi.org/10.1016/j.resourpol.2024.105306

Lin B and Moubarak M (2014). Renewable energy consumption–economic growth nexus for China. Renewable and Sustainable Energy Reviews, 40: 111-117. https://doi.org/10.1016/j.rser.2014.07.128

Liu L, Wang Y, and Wang Z et al. (2022). Potential contributions of wind and solar power to China's carbon neutrality. Resources, Conservation and Recycling, 180: 106155. https://doi.org/10.1016/j.resconrec.2022.106155

Ljungberg J and Nilsson A (2009). Human capital and economic growth: Sweden 1870–2000. Cliometrica, 3: 71-95. https://doi.org/10.1007/s11698-008-0027-7

Majeed A, Wang L, Zhang X, and Kirikkaleli D (2021). Modeling the dynamic links among natural resources, economic globalization, disaggregated energy consumption, and environmental quality: Fresh evidence from GCC economies. Resources Policy, 73: 102204. https://doi.org/10.1016/j.resourpol.2021.102204

Murshed M, Rashid S, Ulucak R, Dagar V, Rehman A, Alvarado R, and Nathaniel SP (2022). Mitigating energy production-based carbon dioxide emissions in Argentina: The roles of renewable energy and economic globalization. Environmental Science and Pollution Research, 29: 16939–16958. https://doi.org/10.1007/s11356-021-16867-y **PMid:34655033**

Nguyen TTH, Phan GQ, Tran TK, and Bui HM (2023). The role of renewable energy technologies in enhancing human development: Empirical evidence from selected countries. Case Studies in Chemical and Environmental Engineering, 8: 100496. https://doi.org/10.1016/j.cscee.2023.100496

Oyegbile MO, Emeke C, and Eze MC (2024). Assessing the economic impacts of renewable energy in Sub-Saharan Africa: A GDP-centric approach. In the SPE Nigeria Annual International Conference and Exhibition, Lagos, Nigeria. https://doi.org/10.2118/221623-MS

Ozcan B and Ozturk I (2019). Renewable energy consumption-economic growth nexus in emerging countries: A bootstrap panel causality test. Renewable and Sustainable Energy Reviews, 104: 30-37. https://doi.org/10.1016/j.rser.2019.01.020

Pegkas P (2014). The link between educational levels and economic growth: A neoclassical approach for the case of Greece. International Journal of Applied Economics, 11(2): 38-54.

Pelinescu E (2015). The impact of human capital on economic growth. Procedia Economics and Finance, 22: 184-190. https://doi.org/10.1016/S2212-5671(15)00258-0

Pesaran MH, Shin Y, and Smith RJ (2001). Bounds testing approaches to the analysis of level relationships. Journal of Applied Econometrics, 16(3): 289-326. https://doi.org/10.1002/jae.616

Pesaran MH, Shin Y, and Smith RP (1999). Pooled mean group estimation of dynamic heterogeneous panels. Journal of the American Statistical Association, 94(446): 621-634. https://doi.org/10.1080/01621459.1999.10474156

Phillips PC and Perron P (1988). Testing for a unit root in time series regression. Biometrika, 75(2): 335-346. https://doi.org/10.1093/biomet/75.2.335

Rafindadi AA and Mika'Ilu AS (2019). Sustainable energy consumption and capital formation: Empirical evidence from the developed financial market of the United Kingdom. Sustainable Energy Technologies and Assessments, 35: 265-277. https://doi.org/10.1016/j.seta.2019.07.007

Rafindadi AA and Ozturk I (2017). Impacts of renewable energy consumption on the German economic growth: Evidence from combined cointegration test. Renewable and Sustainable Energy Reviews, 75: 1130-1141. https://doi.org/10.1016/j.rser.2016.11.093

Rahman MM and Sultana N (2024). Nexus of human development and environmental quality in low-income and developing countries: Do renewable energy and good governance matter? Sustainability, 16(13): 5382. https://doi.org/10.3390/su16135382

Salim R, Yao Y, and Chen GS (2017). Does human capital matter for energy consumption in China? Energy Economics, 67: 49-59. https://doi.org/10.1016/j.eneco.2017.05.016

Shahbaz M, Mateev M, Abosedra S, Nasir MA, and Jiao Z (2021). Determinants of FDI in France: Role of transport infrastructure, education, financial development and energy consumption. International Journal of Finance and Economics, 26(1): 1351-1374. https://doi.org/10.1002/ijfe.1853

Smolović JC, Muhadinović M, Radonjić M, and Đurašković J (2020). How does renewable energy consumption affect economic growth in the traditional and new member states of the European Union? Energy Reports, 6: 505-513. https://doi.org/10.1016/j.egyr.2020.09.028

Talha M, Sohail M, Tariq R, and Ahmad MT (2021). Impact of oil prices, energy consumption and economic growth on the inflation rate in Malaysia. Cuadernos de Economía: Spanish Journal of Economics and Finance, 44(124): 26-32.

Tsamadias C and Prontzas P (2012). The effect of education on economic growth in Greece over the 1960–2000 period. Education Economics, 20(5): 522-537. https://doi.org/10.1080/09645292.2011.557906

Viswanath J, Reddy KLN, and Pandit V (2009). Human capital contributions to economic growth in India: An aggregate production function analysis. Indian Journal of Industrial Relations, 44(3): 473-486.

Yao Y, Ivanovski K, Inekwe J, and Smyth R (2019). Human capital and energy consumption: Evidence from OECD countries. Energy Economics, 84: 104534. https://doi.org/10.1016/j.eneco.2019.104534

Zebra EIC, van der Windt HJ, Nhumaio G, and Faaij AP (2021). A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renewable and Sustainable Energy Reviews, 144: 111036. https://doi.org/10.1016/j.rser.2021.111036

Zhao X, Mahendru M, Ma X, Rao A, and Shang Y (2022). Impacts of environmental regulations on green economic growth in China: New guidelines regarding renewable energy and energy efficiency. Renewable Energy, 187: 728-742. https://doi.org/10.1016/j.renene.2022.01.076