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Research article

Renewable energy transition, financial development, and sustainable development in Saudi Arabia: evidence from advanced econometric techniques

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Abstract: In this research, I analyzed the relationship between the renewable energy transition, financial development (FD), and sustainability in Saudi Arabia over a period covering the years 1990 through 2024. My primary purpose of this research was to determine the impact that financial, environmental, and institutional factors have on the transition to renewable energy under the auspices of Saudi Vision 2030. To achieve this, I utilized time-series data over a span of 30 years and employed advanced econometric methods, including the Autoregressive Distributed Lag (ARDL) Bounds Testing Technique, Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS). All three techniques revealed statistically significant relationships between the dependent and independent variables in the short-run and long-run. Therefore, the results were replicated several times in the empirical section of the study. The findings support the existence of a long-term stable correlation between independent and dependent variables, particularly the positive influence of financial services development, human capital accumulation, improvements in energy efficiency (EE), increased government spending on renewable energy, greater trade openness, and more foreign direct investment (FDI) on the shift to renewable energy. However, carbon dioxide (CO2) emissions and oil rents have a negative impact on the shift to renewable energy due to the reliance on fossil fuels. Moreover, the evidence also demonstrates that the renewable energy transition is a key source of structural diversification of sustainable development within Saudi Arabia's economy. As recommendations for practice, I suggest to strengthen green financing instruments, expand renewable

energy investments, enhance institutional quality, and continue to develop human capital to accelerate the renewable energy transition.

Keywords: Renewable energy transition; Financial development; Sustainable development; Saudi Arabia; ARDL

1. Introduction

Over the years, there have been significant changes and restructuring of the global economy, mainly driven by economic factors, as well as factors related to climate change, exploitation of natural resources, and the development of a sustainable economic framework. In particular, the increase in the use of fossil fuels has led to depletion of natural resources, economic risks, and a premium on carbon credit. In this respect, there has been a clear recognition of the role of renewable energy as a fundamental component of a sustainable economic framework, capturing concepts such as the preservation of natural resources, economic risks, and sustainable economic growth [1]. In academic literature, there is a clear recognition of the need to move from a fossil fuel-based carbon resource usage model to a usage model of renewable energy, such as solar, wind, and biofuels [2,3]. Moreover, studies emphasize that renewable energy transition contributes significantly to environmental sustainability, energy security, and low-carbon economic growth, particularly in developing and oil-dependent economies [1,4].

Current trends suggest that the mitigation of global warming has evolved from an aspiration for the future into an operational reality with countries working hard to realize carbon-neutral targets. The Paris Climate Conference of 2015 and the United Nations Sustainable Development Goals for 2030 provide guidelines for the future in which renewable energy will be the defining factor. Currently, the world is spending a historic high on clean tech, with solar and wind energy being developed at prices comparable to fossil fuels. However, oil-rich countries have a challenge in that their economies are largely based on hydrocarbon energy.

Saudi Arabia is used as a case study in this context. Being one of the top oil-producing countries in the world, Saudi Arabia has made attempts to transform its economy to be more sustainable by aligning itself with the vision for 2030, which brings together economic growth and sustainable development. This includes the development of renewable energy resources, increasing efficiency in the energy sector, and developing sustainable finance to reduce oil dependence [5]. The government of Saudi Arabia has shown its commitment to creating a better and more sustainable future through the Green Saudi Initiative and the NEOM Solar Project. Part of this plan includes making significant investments in technologies to promote sustainability [6,7]. Additionally, several sources state that Saudi Arabia plans to create nearly half of its total electricity needs from renewable resources by 2030 as part of its plan for long-term transition to energy sourcing [8].

In recent years, Saudi Arabia has in a way strengthened its renewable energy policies by pushing forward national renewable energy programs, public private partnerships, and regional cooperation steps under the Green Middle East Initiative. The Kingdom is looking to pull in nearly 50% of its electricity from renewable sources by 2030, and later reach carbon neutrality by 2060. Additionally,

the Public Investment Fund along with the Saudi Electricity Company have rolled out financial instruments for large scale solar and wind projects, with backing from international organizations such as IRENA and the World Bank.

Renewable energy transition efforts are behind expectations, though they have moved forward in some respects in Saudi Arabia. New research suggests that growing financial development (FD) is very important for driving renewable energy transition and supporting the Sustainable Development Goals (SDGs). An effective financial system has the capacity to provide resources for domestic and foreign investments, provide support for investments in renewable energy, and support technological innovation efforts within the renewable energy industry [9,10] (Although there are some barriers, well-developed capital markets and a well-functioning banking system can provide the financial intermediation needed to boost environmentally sustainable investment, leading to better sustainability results.

The connection between macroeconomic and institutional elements and developments in renewable energy goes well beyond economic development and into those areas previously mentioned at high correlation magnitudes. Human capital, for example, supports the adoption of renewables through technology innovation and practical knowledge associated with development of skilled labor, not simply through theory. Moreover, by reducing the operating costs of energy use through increased efficiency, EE will also provide increased economic attractiveness of renewable energy due to the improved efficiency with which energy is consumed. Trade openness (TR) and foreign direct investment (FDI) can accelerate the diffusion of technologies leading to improved access to the renewable energy infrastructure that will also facilitate greater adoption of renewable energy. Likewise, government expenditures (GOVs) on environmental sustainability, renewable energy production capacity, and green investment incentives will have a strategic impact on encouraging the transition to renewable energy. In contrast, increasing CO2 emissions and a dependence on rent generated by oil resources will delay the adoption of renewable energy since these factors keep fossil-fuel dependency intact and prevent broader-based diversification of the economy. Therefore, it is important to identify how financial, environmental, and institutional factors interact to achieve sustainable development in Saudi Arabia.

Moreover, the empirical conceptual framework/current literature dealing with the Kingdom of Saudi Arabia lacks an adequate connection between FD, renewable energy transition, and sustainable development. Researchers have typically focused on either energy consumption or economic growth with little consideration of the relationship among the three.

Even with the progress that is happening in Saudi Arabia for sustainability and renewable energy development, some issues keep showing up and they slow the idea of balanced sustainable growth. For example, there is high use of fossil fuels, energy sources are not diversified enough, and financing works in ways that are often not very efficient. Although investment in renewable energy has increased considerably, the transition toward sustainability remains insufficient. Consequently, there remains a significant gap in understanding how FD can support Saudi Arabia's transition toward renewable energy and contribute to the achievement of Sustainable Development Goals.

In this study, I aim to explore the correlation between sustainable development and renewable energy transition, as well as relate these two concepts to FD in Saudi Arabia from 1990–2023. To achieve this, I will investigate how factors such as, human capital, FD, EE, FDI, trade openness, GOV,

carbon dioxide (CO2) emissions, and oil rents affect the movement of renewable energy toward development over the short term and long term. The long-term growth patterns and causal factors that exist among the variables being studied will be determined through the use of advanced econometric methodologies- particularly Autoregressive Distributed Lag (ARDL), Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS) estimating techniques.

The motivation behind selecting this topic stems from the growing global and domestic need to balance economic development with environmental sustainability. The Saudi Arabian context requires renewable energy transition since it serves two purposes: Protecting the environment and decreasing oil revenue dependence while supporting long-term economic development. The transition process needs a financial system which operates with high efficiency to enable sustainable investments and green economic transformation.

The research work presents multiple significant scientific contributions to its respective field. I evaluate three major areas through an integrated econometric framework that utilizes current WDI and IEA database annual data from both organizations. The study presents new research data about Saudi Arabia, which supports the Vision 2030 and Sustainable Development Goals (SDGs) objectives and policy recommendations that will help policymakers develop effective green finance systems while decreasing carbon emissions and boosting renewable energy deployment to achieve SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

Figure 1 provides the theoretical framework of this study, which illustrates how financial, institutional, environmental, and macroeconomic factors interact with one another to impact renewable energy transition and sustainable development in Saudi Arabia.

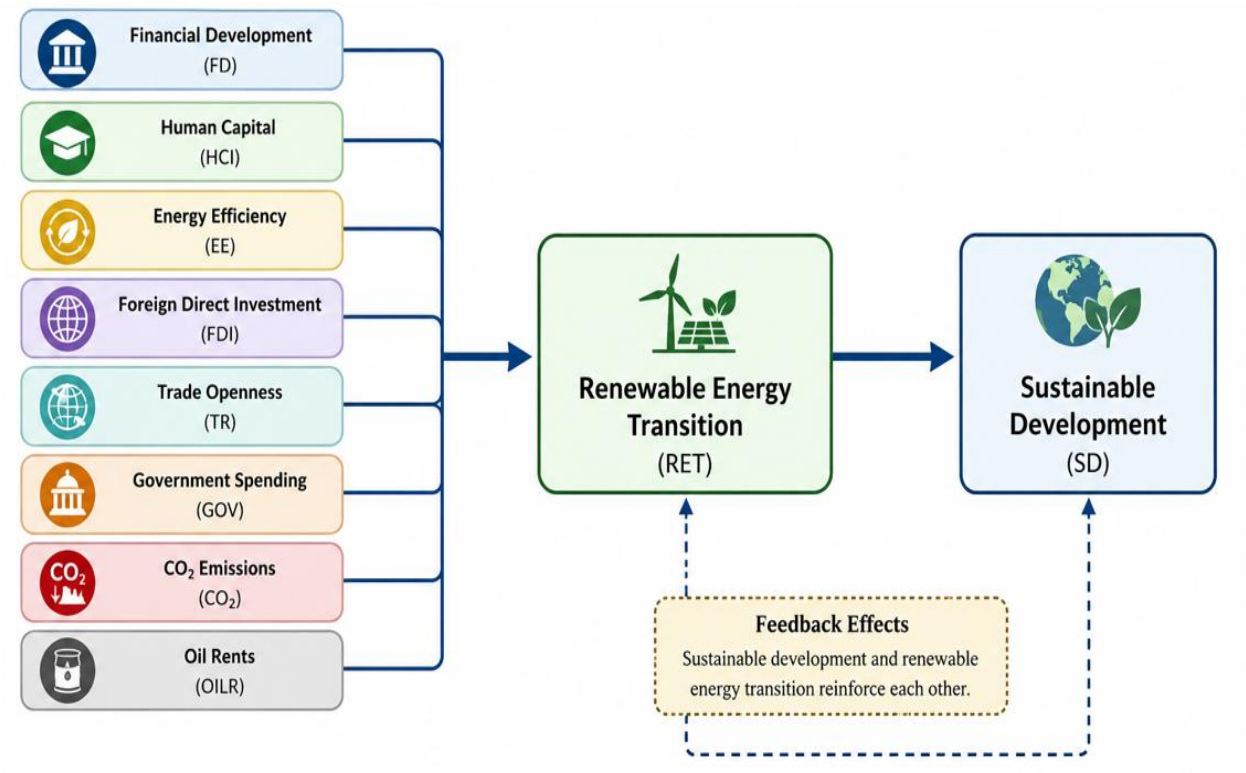


Figure 1. Conceptual framework of the study.

The remainder of the paper is organized as follows: In Section 2, I review the relevant theoretical and empirical literature. In Section 3, I present the conceptual framework, data, variables, and econometric methodology. In Section 4, I discuss the empirical findings and their interpretations. Finally, in Section 5, I conclude the study and present policy implications and recommendations.

2. Literature review and theoretical background

2.1. Theoretical background

There are a few theoretical paradigms that try to frame the relationship between renewable energy, FD, and sustainable economic growth in a relevant context. One major perspective is Endogenous Growth Theory; it was set out by Romer [11] and further pushed by Howitt and Aghion [12]. In short, the theory argues that spending on innovation, new technologies, and human capacity (including areas linked to renewable energy) can raise overall efficiency in the economy, mainly through productivity effects, so sustainable growth can keep going. Another angle is the Environmental Kuznets Curve (EKC). This idea was first put forward by Grossman and Krueger [13], and additional evidence and interpretations were provided by Stern [14]. In general, the EKC suggests that as economies develop, environmental degradation rises at first until a kind of turning stage is reached, and then the degradation begins to fall. Renewable energy here becomes a key lever for shifting the curve downward because it supports cleaner production and can be expanded through technological investment. For Saudi Arabia, the strategic road toward that EKC turning point is often linked to Vision 2030, which includes building a more robust financial system, accelerating technological progress, and promoting green investment policies, all aimed at a more sustainable form of growth.

Endogenous Growth Theory argues that growth comes from inside the system, not from some outside push, and there is this steady flow of innovation, technological progress, and investments into human capital that end up acting like the main drivers. Thus, steady financing for clean technologies, R&D, and education will help an economy follow a path of sustained long-term expansion. The central point is that clean energy is not only a technical input, but it also becomes part of the innovation result, raising overall outcomes via better efficiency and productivity. In simple terms, durable economic growth shows up because the energy mix gets rearranged, rather than growth happening first and then later being followed by a change in energy sources.

However, the FD hypothesis, first proposed by Schumpeter [15] and later refined by King and Levine [16], points to how the financial systems push economic growth. In other words, it happens through things like raising funds in an efficient, more or less, smart manner, putting those funds to work, and using resources optimally, not just randomly. When these financial systems operate at their best, the financial sector turns into the driving force behind green finance development, sustainability efforts, and the uptake of renewable energy, all for the bigger goal of reaching economic growth in a sustainable way.

This direction can also be described as the Green Finance Theory; it treats the financial sector as a key mechanism for achieving the Sustainable Development Goals. Thus, the connection between FD and the transition toward renewable energy, for the sake of sustainable economic growth, feels relevant. The idea is that financial institutions can help speed up the movement of energy, reduce environmental

harm, and encourage technological innovation. It is especially meaningful for economies in resource rich countries, like Saudi Arabia, where it can manage to financially support the move to a low carbon economy, and then, in turn, lower the dependence on fossil fuel consumption.

For the study, different theoretical frameworks will guide the discussion about economic growth and how FD links up with the shift toward renewable energy adoption using Endogenous Growth Theory, the Environmental Kuznets Curve, and Green Finance Theory.

2.2. Empirical literature review

Researchers have generally been interested in the relationship between sustainable development, finance, and renewables. Research from Sadorsky [17] initially highlighted the link between economic growth and the use of renewable energy, especially in OECD and Developing countries. The findings of the earlier studies were proof of the potential of renewable energy as a contributor to economic development, conceptually and through empirical evidence. The subsequent development of this research area has expanded the scope of renewable energy economics to include the relationship between FD and sustainable development. For instance, through the use of a panel cointegration approach, Shahbaz et al. [18] demonstrated that renewable energy has a positive influence on economic growth; they also found that FD positively contributes to both of these areas by assisting with resource mobilization for the renewable energy sector. The positive contribution of FD to energy and economic growth (i.e., the energy-growth nexus) was also substantiated by Acheampong et al. [19] and Destek and Sinha [20]; however, their contributions were primarily through eliminating credit constraints, which facilitate the development of renewable energy resources.

What stands out across all these analyses is a dominant thread that accounts for all the results, which is that FD increases the usage of renewable energy while it becomes more apparent over time. This can be evidenced by Elzaki [10] who noted that FD enables more renewable energy consumption, with its long-run impact increasing, thus stressing FD's significance in managing the energy sector's transition. On a similar theme, Anton and Nucu [21] noted that capital market development may be more efficient in increasing renewable energy consumption compared to banking sector development, especially when concentrated on Europe as a region. This is supplemented by, Alharthi et al. [22] noting that financial inclusion, or rather access and consumption rates, can enhance renewable energy consumption in developed and developing nations. On a related theme, stressing or noting sustainable growth benefits alongside environmental benefits, Adebayo et al. [23] noted that access to renewable energy aids sustainable growth over long periods while reducing CO2 emissions using a green innovation approach accordingly. Note that this is consistent with a parallel body of research by Mukhtarov et al. [24], noting that an increased dependence on renewable energy helps in reducing carbon emissions but results in increased environmental degradation when fossil fuels are utilized.

Islam et al. [25] studied how renewable energy technologies, which included solar photovoltaics and electric vehicles and wind energy sources, affect environmental safety in Saudi Arabia's Hail Region. They used survey data from 275 respondents and applied the PLS-SEM method to demonstrate that wind energy positively affects environmental safety when strong regulatory governance and public awareness provide support. The research showed that solar energy and electric vehicle technologies did not create direct effects, which remained unaffected by moderation effects. The research results

demonstrated that age serves as the only demographic factor that affects study results while gender and occupation and education do not show any statistical importance. The researchers conclude that regulatory governance and public awareness need strengthening because these factors serve as essential requirements for achieving better results with renewable energy technologies while enhancing environmental sustainability throughout the region.

Islam et al. [26] studied how five factors, including FD, R&D, ICT, globalization, and economic growth, work together to promote renewable energy transition in South Asian countries from 1990 until 2023. The researchers used advanced econometric techniques to demonstrate that FD works as a positive factor for renewable energy transition, which especially benefits from its initial stages. The positive impact of the relationship between finance and R&D and globalization is diminished because of insufficient coordination between these three elements. The research demonstrated that ICT development creates barriers to renewable energy adoption while economic growth provides support for the long-term transition process. The authors concluded that effective and integrated policies are necessary to direct financial and technological resources toward sustainable energy development.

Studies continue to reveal that globalization and sound financial systems form the backbone of renewable energy transition. Moreover, Khan et al. [27], using panel data of developed and emerging economies, illustrated that investment in research and development, renewable energy, and FD complement each other in augmenting green economic growth.

However, studies are illuminating FD in terms of its contribution to the shift to renewables in an even brighter light. For example, state-of-the-art analysis reveals the impact of green financial products on the energy sector, improving the efficiency of investments in renewables. FD in 167 countries has been found to affect the shift to renewable energy in different ways, as revealed by global panel data. Quantile regression studies have also shown that FD is not homogeneous in its impact on renewable energy. For oil-exporting economies, FD in terms of its impact on economic growth is significant in affecting the shift to renewable energy. In terms of FD in China and the European Union, FDIs and green financial instruments are significant in promoting economic growth.

Despite these contributions, few researchers have integrated FD, renewable energy transition, and sustainability within a unified framework for Saudi Arabia.

2.3. Conceptual and theoretical frameworks

The relationship between FD and renewable energy transition and sustainable development depends on several essential factors. FD improves access to capital and facilitates investment in renewable energy through green financial instruments and sustainable financing mechanisms that enable the growth of renewable energy initiatives.

Human capital is an essential factor that helps boost the adoption of renewable energy by developing innovation capabilities and technical expertise and enabling the spread of cutting-edge technologies. Renewable energy transition benefits from TR and FDI because these factors enable technology transfer and provide access to advanced energy systems.

The transition process receives support from GOV through its funding of research and development, infrastructure development, and renewable energy incentives. The energy transition

process faces delays because oil rent dependence leads to increased fossil fuel use, which prevents economic diversification.

The study shows how financial and institutional and economic factors work together to determine the development of renewable energy and sustainable development in Saudi Arabia.

3. Methodology

3.1. Data and variables

In this study, annual figures from 1990 to 2024 were used to probe how FD and sustainable development, together, might shape Saudi Arabia's renewable energy transition. The analysis leans on different macroeconomic and environmental indicators pulled from well-known international sources. The data came from the WDI database, the IRENA, and the IEA, which resulted in a total of 35 yearly observations.

All variables selected were grounded in theoretical rationale and practical relevance to the literature framework on financial sustainability, FD, and the transition to renewable energy resources. The variables were annual in frequency to quantify the structural properties of the Saudi economy over a long-term period in an annual incremental fashion. To improve the stability of the results and facilitate interpretation, the continuous variables were transformed into natural logarithmic form except ratios, percentages, and growth rates, which were in percentages.

The dependent variables proxied with the transition into renewable energy sources and were measured by either the percentage of renewable energy sources in total power production or, alternatively, the renewable energy source capacity per capita. Financial development (FD) was the main explanatory variable and was measured by domestic credit to the private sector as a percentage of GDP.. Sustainable development indicators were also used, like the Human Capital Index (HCI), EE, and CO2, though not all in the same way. As for the control variables, these included economic growth (GDPG), TR, FDI, GOV, and oil rents (OILR). The OILR acted as a proxy for energy dependence, so it was connected but indirect. Variables were chosen to represent the complex character of the transition to renewable energy sources, where FD and the dimensions of sustainability were involved. FD represented the ability of banking and financial systems to provide funding sources for renewable energy projects; on the other hand, the dimensions of sustainability represented developments in all areas of life and the environment. Control variables were used to extract the total impact of financial and sustainability developments since trade volumes, public spending, and international oil-market conditions were constant.

Table 1. Summary of variables.

Category	Variable	Symbol	Measurement / Definition	Source	Expected Sign
Dependent Variables	Renewable energy transition	RET	Share of renewable electricity in total generation (%)	IRENA / IEA	—
Financial development	Domestic credit to private sector	DCPS	% of GDP (proxy for financial depth and intermediation)	WDI	+
Sustainable development	Human Capital Index	HCI	Index (0–1) representing education and skills	WDI	+
	Energy efficiency	EE	GDP per unit of energy use (constant 2015 PPP US$/kg oil eq.)	WDI	+
	Carbon dioxide emissions	CO2	Metric tons per capita	WDI	−
Economic control	Economic growth	GDPG	Annual growth rate of real GDP (%)	WDI	±
Openness	Trade openness	TR	(Exports + Imports)/GDP (%)	WDI	+
External investment	FDI inflows	FDI	Net foreign direct investment (% of GDP)	WDI	+
Fiscal policy	Government expenditure	GOV	General government final consumption (% of GDP)	WDI	±
Energy dependence	Oil rents	OILR	Oil rents reflect how much countries benefit economically from oil resources. Oil rents = (Value of crude oil production − Production cost) / GDP × 100	WDI	

3.2. Model specification

The empirical model developed in this analysis was utilized to examine the dynamic relationship between the process of renewable energy transition, FD, and sustainable development in Saudi Arabia. Based on the theoretical framework previously outlined, this model considered the direct and indirect contributions of FD on renewable energy transition, but subject to a list of control variables, which included structural elements of a Saudi economy. The formula for this model is outlined as follows:

$$RET_t = f(FD_t, HCI_t, EE_t, CO2_t, GDPG_t, TR_t, FDI_t, GOV_t, OILR_t)$$

In this paper, I introduce certain key variables: RET refers to renewable energy transition; FD to FD; HCI to human capital; EE to energy efficiency, CO_2 to environmental pressure; GDPG to economic growth; TR to trade; FDI to foreign direct investment, GOV to government spending; andOILR represents oil rents (% of GDP) and is used as a proxy for the economy's dependence on oil resources. . This functional form was consistent with earlier studies, such as those in Shahbaz et al. [18], Acheampong et al. [19], and Adebayo et al. [23], who applied a comparable modeling approach to analyzing the relationship between sustainability, renewable energy transition, and FD.

The general consensus in these studies was that financial institutions play a vitally mediating role, facilitating investment in renewable energy while supporting overall financial growth. To this end, I applied a log-linear form to our modeling so that the coefficients extracted from my results may be identified as elasticities and to assist in mitigating any effects of heteroscedasticity evident in my dataset. Thus, I proposed the following empirical model:

$$ln(RET_t) = \alpha_0 + \beta_1 ln(FD_t) + \beta_2 ln(HCI_t) + \beta_3 ln(EE_t) + \beta_4 ln(CO2_t) + \beta_5 ln(GDPG_t) + \beta_6 ln(TR_t) + \beta_7 ln(GOV_t) + \beta_8 ln(OILP_t) + \varepsilon_t$$

where (RET_t) denotes renewable energy transition; (FD_t) represents financial development; (EE_t) denotes energy efficiency; ($CO2_t$) refers to carbon dioxide emissions; ($GDPG_t$) represents economic growth; (TR_t) denotes trade openness; (FDI_t) denotes foreign direct investment; (GOV_t) represents government expenditure; ($OILR_t$) denotes oil rents; (HCI_t) represents the human capital index; (α_0) is the intercept term; (β_i) are the long-run coefficients; and (ε_t) is the error term.

Variable Justifications and Expected Signs

In this model, every variable was supported by robust theoretical justification and, in turn, corresponded to robust empirical evidence based on previous research. My main measure of progress was the RET, which may be based on either the share of electricity supplied by renewables in total supply or renewable capacity per person. It is one of the standard variables in the literature to monitor how the adoption of clean energy progresses in developed and less developed countries [23].

However, assume that FD will have a positive relationship with the adoption of renewable resources, meaning $\beta_1 > 0$. Studies by Shahbaz et al. [18], validate the point that better financial systems will increase the availability of credit, thereby boosting private sector investments in the low-carbon economy. In the case of Saudi Arabia, enhancing its financial system through green bonds is seen as essential to transitioning to the LCE.

There are two large sustainability indicators: EE and HCI. Research from Destek and Sinha [20] and Adebayo et al. [23] concluded that countries with higher human capital resources are more innovative and can implement RET successfully, thus owing to higher knowledge and skillsets. Similarly, higher EE (β3) enhances resource-use efficiency, thereby improving the allocation and utilization of resources. This notion is supported by Acheampong et al. [19], who proved the correlation between EE and sustainable output for developing countries.

The amount of CO_2 we emit acts as a deterrent toward renewable energy acceptance and proceeds in the direction of sustainable development. In a research point of view, the effect of it always tends to be negative ($\beta_4 < 0$). It is not mere theory but practical; Grossman and Krueger [13], Stern [14], and Adebayo et al. [23] proved that higher emission of CO_2 causes environmental degradation and hampers the process of green development. On the other hand, when emissions are reduced, it helps indirectly toward renewable energy switching because policymakers and other stakeholders create a sharper focus.

Economic growth (GDPG) could have a non-significant effect (β5 ±). On the one hand, growth could boost incomes and investable resources, but, on the other hand, growth fueled by non-renewable energy could boost the demand for energy and pollution. Such double-edged potentialities are

consistent with the Environmental Kuznets Curve Hypothesis, which has been verified by researchers such as Acheampong et al. [19].

TR and FDI are expected to have a positive effect on the process of the transition to renewable energy sources: β6>0, β7>0. According to research by Fang et al. [28] and Kim et al. [29] international commerce and FDIs streamline the financial investment and knowledge transfer processes, increasing the availability and accessibility of green technologies.

GOV is another significant key factor in my model based on fiscal policy. Studies by Alharthi et al [22] and Sun et al., [9] showed that GOV in green and research activities helps increase the spread of renewable energy sources. If such expenses are made in non-productive and fossil fuel-based sectors, they could be zero or negative in effect (β8 ±).

Last, oil prices (OILR) used to represent energy dependence could have a mixed result (β9 ±). According to Mukhtarov et al. [24] and citing the works of Adebayo et al. [23] in relation to the rise in oil prices, there could be a great incentive to diversify or develop energy resources. In the Saudi Arabian case, however, high oil prices will result in increased earnings, thus reducing priority to develop other energy sources.

3.3. Estimation methods

The empirical approach used in this study combined econometric procedures for the analysis of short- and long-term relations between the renewable energy transition, FD, and sustainable development in the Kingdom of Saudi Arabia. In this context, every step in the research methodological process helped confirm the statistical and economic consistency of the results obtained. The approach involved several stages: testing for stationarity, cointegration analysis, the analysis of long- and short-term relations, testing for causality, diagnostic checks, and robustness analysis.

The first level involved the determination of the stationarity and order of integration of each and every variable in the time series process. The Augmented Dickey-Fuller (ADF) test was employed to examine the stationarity properties of the variables:

$$\Delta Y_t = \alpha + \rho Y_{t-1} + \sum_{i=1}^{p} \gamma_i \, \Delta Y_{t-i} + \varepsilon_t$$

In the above equation, Y_t is the variable of interest, ΔY_{t-1} is the first difference of Y_t, and p is the lag order used to counter the problem of serial correlation. The null hypothesis (H_0: ρ = 0) indicates the presence of a unit root or non-stationarity.

In addition, the Zivot and Andrews [30] test was employed to account for a possible structural break associated with the Saudi Vision 2030 reforms introduced in 2016. Given the order of integration, the next step was to check for the existence of long-run relationships between the variables. I used the ARDL Approach of Pesaran et al [31]. The ARDL approach is suitable for small sample sizes and can be applied when variables are integrated of order I(0) and I(1). The ARDL can be written as:

$$\Delta Y_t = \alpha_0 + \sum_{i=1}^{p} \beta_i \, \Delta Y_{t-i} + \sum_{i=0}^{q} \gamma_i \, \Delta X_{t-i} + \phi_1 Y_{t-1} + \phi_2 X_{t-1} + \varepsilon_t$$

where Y_t denotes the dependent variable representing the renewable energy transition, and X_t represents the vector of independent variables, including FD, human capital, EE, CO_2 emissions, and other control variables. The F statistic that comes from the bounds test was set against the relevant lower and upper critical bounds. If the F statistic goes beyond the upper bound, the existence of a long-term relationship is verified. Thereafter, once cointegration is confirmed, the ARDL model is reshaped into an Error Correction Model (ECM) to look at short-run movements and how fast the system adjusts back toward the long-run equilibrium. The ECM equation form can be stated like this:

$$\Delta \ln(RET_t) = \alpha_0 + \sum_{i=1}^{p} \beta_i \, \Delta \ln(RET_{t-i}) + \sum_{i=0}^{q} \gamma_i \, \Delta X_{t-i} + \delta ECT_{t-1} + \varepsilon_t$$

where ECT_{t-1}represents the lagged error-correction term, and its coefficient measures the speed at which short-run deviations converge to the long-run equilibrium. Coefficient δ is a measure of adjustment speed, implying convergence toward a long-run solution after a disturbance in the short run. A negative and statistically significant coefficient confirms the existence of a long-run equilibrium relationship. To ensure the validity of the ARDL findings, I also incorporated two alternative long-run techniques: FMOLS and DOLS. FMOLS and DOLS were employed to ensure the robustness of the long-run estimations.

The FMOLS technique was introduced by Phillips and Hansen [32] to correct for endogeneity and serial correlation problems in cointegrated systems. Then, Stock and Watson [33] introduced the DOLS technique based on the leads and lags of the regressors in their multiple forms.

$$Y_t = \alpha + \beta X_t + \sum_{i=-k}^{k} \theta_i \, \Delta X_{t-i} + \varepsilon_t$$

The studies conducted by Shahbaz et al. [18], Acheampong et al. [19], and Adebayo et al. [23] are some of the applications of the estimators in validating the ARDL bounds test and establishing the long-run relationship between the variables.

4. Empirical results and discussion

My purpose of this section is to provide the empirical findings. To ascertain the type of data and validate the use of the ARDL technique, I begin this section with the implementation of preliminary tests for unit roots and cointegration. I then proceed with the application of the ARDL test for the estimation of the long-run relationships. The examination of the short-run dynamics is conducted by employing the ECM. Last, the validity of the long-run estimates is further verified by the application of the FMOLS and DOLS.

4.1. Descriptive statistics and correlation analysis

Based on a sample size of 35 observations, Table 2 shows the descriptive statistics for the variables that go into the empirical analysis. All variables are written in their natural logarithmic form, so everything is comparable across the board. Looking at the numbers, the mean and the median for most variables seem close together, implying a fairly level pattern and not much indication of strong asymmetry in the data.

For ln(RET), the mean points to a relatively high level of renewable energy transition happening across the study period. Additionally, the positive mean values for ln(EE), ln(FD), ln(GOV), ln(HCI), ln(OILR), and ln(TR) suggest improvements in EE, FD governance quality, human capital, oil rents, and TR over the sample period. Moreover ln(FDI) shows a negative mean value (-0.5469), which hints at weak or somewhat erratic FDI inflows during some periods, which is not exactly stable.

In terms of dispersion in the data, moderate levels of variability can be seen across most variables, particularly those based on the example variables; however, ln(FDI) and ln(GDBG) have much higher coefficients of deviation than other variables, which indicates that these two variables are less consistently distributed, with more variation throughout the analysis. This implication could indicate possible macroeconomic instability or other influences from outside the country. Conversely, variables such as ln(CO2) and ln(EE) produce much less variability than ln(FDI) and ln(GDPG) through the analysis, which indicates that they likely experienced less fluidity through the study's timeframe. Overall, the descriptive statistics provide a general, and somewhat preliminary, idea of how much variability is present, and the extent to which the variables are influenced by different external factors during the timeframe examined in the analysis.

Table 2. Descriptive statistics.

Variables	Mean	Median	Maximum	Minimum	Std. Dev.
ln(RET)	9.1850	9.1203	9.5020	8.9236	0.1778
ln(CO2)	3.0065	3.0315	3.1935	2.6858	0.1121
ln(EE)	2.0592	2.0599	2.2661	1.8911	0.0931
ln(FD)	3.5071	3.5672	3.9959	2.6961	0.3933
ln(FDI)	-0.5469	-0.3416	1.1585	-4.5407	1.2740
ln(GOV)	3.1717	3.1552	3.5309	2.8738	0.1415
ln(GDPG)	0.9839	1.1953	2.4850	-1.1657	1.0411
ln(HCI)	2.0980	2.1082	2.4557	1.7183	0.2457
ln(OILR)	3.4837	3.4450	3.9906	2.7713	0.2990
ln(TR)	4.2205	4.2063	4.5654	3.8614	0.1813

As seen in Table 3, there are positive correlations between lnRET and lnFD, and lnHCI, indicating that improvements in financial systems and increases in human capital are associated with increasing levels of renewable energy development. Conversely, there are negative correlations between lnGOV and lnTR, indicating that improvements in governance quality and trade openness are associated with decreasing levels of renewable energy development; therefore, it can be concluded that a reverse relationship exists between these two factors over the time periods examined.

While there is a positive correlation between lnRET and lnCO2, the correlation is only moderately strong, suggesting that the overall trend toward renewable energy may still occur while having

increasing levels of emissions. In addition, the correlation coefficient between lnRET and lnFDI indicates a weak positive relationship; therefore, you cannot reliably conclude that an increase in FDI directly correlates to an increase in renewable energy development.

There is a strong positive correlation between lnFD and lnHCI of 0.9542; hence, there is a clear relationship between FD and accumulation of human capital. Again, there is also a high correlation between lnRET and lnHCI at 0.9546. These high correlation values (indicating close relationship) might also cause a concern regarding the possible presence of multicollinearity (when the regressors are too talkative) or significant amount of overlap in regressing HCI, RET, and FD, for example, to increase their statistical significance through multicollinearity. However, further investigation is conducted through variance inflation factor (VIF) calculations for all explanatory variables to assist in providing increased confidence of the regression coefficients, and that all are supported by statistical evidence or uses of the regression coefficients. Thus, despite experiencing multicollinearity, HCI and FD are substantiated as having stable coefficients and all other outcomes are interpreted statistically.

Table 3. Correlation matrix.

Variables	ln(RET)	ln(CO2)	ln(EE)	ln(FD)	ln(FDI)	ln(GOV)	ln(GDPG)	ln(HCI)	ln(OILR)	ln(TR)
ln(RET)	1.0000									
ln(CO2)	0.3283	1.0000								
ln(EE)	0.1494	-0.0746	1.0000							
ln(FD)	0.9039	0.2168	0.0794	1.0000						
ln(FDI)	0.2160	-0.2116	0.3652	0.2137	1.0000					
ln(GOV)	-0.3940	-0.1972	-0.4273	-0.5523	-0.3741	1.0000				
ln(GDPG)	0.0522	0.0198	0.2112	0.0218	0.1731	-0.1170	1.0000			
ln(HCI)	0.9546	0.3079	0.2022	0.9542	0.2108	-0.5473	0.1520	1.0000		
ln(OILR)	-0.1654	0.1226	-0.3248	0.0198	-0.0241	-0.1760	0.2042	-0.0620	1.0000	
ln(TR)	-0.4483	0.0893	0.0928	-0.2473	-0.1111	-0.2681	0.3039	-0.2563	0.6425	1.0000

4.2. Multicollinearity test (VIF analysis)

The VIF test performed in Table 4 provides a way to evaluate whether multicollinearity exists between the independent explanatory variables in the model. Overall, all but a few variables demonstrate VIFs within acceptable ranges; therefore, multicollinearity does not appear to be an issue for most of the independent explanatory variables. However, the VIFs for HCI and FD (25.34 and 23.17, respectively) indicate that there is multicollinearity among HCI and FD, as well as with respect to the other independent explanatory variables within the same model. The high VIFs can also significantly affect the accuracy of the coefficients and the stability of the estimated coefficients when applying the regression analysis.

Nevertheless, the remaining variables show relatively low VIF values ranging between 1.58 and 3.50, confirming that they do not contribute substantially to multicollinearity problems. In addition, the mean VIF value of 7.24 remains below the critical threshold of 10, suggesting that multicollinearity is moderate at the overall model level.

Overall, although multicollinearity is detected particularly between HCI and FD, the estimated coefficients remain economically interpretable and statistically stable. In future studies, researchers

may consider alternative model specifications, variable transformations, or dimension reduction techniques to further minimize potential overlap among highly correlated explanatory variables.

Table 4. VIF Test.

Variable	VIF	1/VIF
HCI	25.34	0.039
FD	23.17	0.043
TR	3.50	0.286
GOV	2.86	0.349
OILR	2.86	0.350
EE	2.46	0.406
GDPG	1.74	0.575
FDI	1.62	0.618
CO2	1.58	0.634
Mean VIF	7.24	—

Note: VIF values above 10 indicate potential multicollinearity problems.

4.3. Unit root and structural break tests

Table 5 presents the results of the conventional unit root tests, namely the ADF and Phillips–Perron (PP) tests, together with the Zivot and Andrews [30] structural break unit root test. These tests are employed to examine the stationarity properties and integration order of the variables included in the model while accounting for possible structural changes during the study period.

The results from the conventional ADF and PP tests indicate that most variables are non-stationary at their level forms, as the null hypothesis of a unit root cannot be rejected. However, after taking the first difference, most of the variables become statistically significant at the 1% significance level, implying that they are integrated of order one, denoted as I(1). Specifically, ln(CO_2), ln(EE), ln(FD), ln(GOV), ln(HCI), ln(OILR), ln(RET), and ln(TR) are stationary after first differencing. This suggests that shocks affecting these variables have temporary effects and that the variables converge toward their long-run equilibrium paths over time.

In contrast, ln(FDI) and ln(GDPG) are stationary at level form under the ADF and PP tests, as evidenced by their statistically significant test statistics at conventional significance levels. These variables are therefore integrated of order zero, I(0), indicating that they fluctuate around a stable mean without requiring differencing.

Because traditional unit root tests are unable to consider possible structural breaks that may exist for many macroeconomic and energy variables, the Zivot and Andrews [30] test is also performed. The Zivot and Andrews test is relevant, as it enables one endogenous structural break in the intercept and trend of the series. The Saudi Arabian economy has experienced a number of major structural and policy changes during the sample period, such as oil price shocks, financial reforms, and the implementation of the Saudi Vision 2030 plan, making the testing process particularly relevant for understanding these characteristics of the Saudi economy.

The same check results from previous checks using ADF and PP tests for ln (FDI), ln (GDPG), and ln (CO_2), meaning that these three series are all stationary at their levels, even though I test for structural breaks in a proper manner; therefore, they continue to be I(0) series. On the other hand, the ln(RET), ln(FD), ln(EE), ln(TR), ln(GOV), ln(OILR), and ln(HCI) time series do not show stationarity at their levels. They do have I(1) integrational orders, as seen by the first-difference calculation.

With respect to the estimated structural change dates, they will vary from variable-to-variable and, in general terms, will all fall somewhere between 1996 and 2018. Practically speaking, these structural periods match with some significant economic/institutional changes related to the Saudi economy/energy markets, such as, but not limited to, international oil price fluctuations, global financial disruptions, energy market reforms, and the introduction of larger sustainability/diversification initiatives under Vision 2030.

The empirical results show mixed modes of integration for the variables studied. Some of the variables are integrated of order zero (I(0)), and some are integrated of order one (I(1)). The important thing is that none of the variables are integrated of order two (I(2)). This means that it is valid to use the ARDL bound testing approach because it is designed to accommodate a combination of I(0) and I(1) variables. In addition, structural breaks are taken into account and assist in providing reliable and robust evidence of stationarity and more accurate long-run estimates in future econometric analyses.

Table 5. Unit root and structural break test results.

Variable	ADF (Level)	PP (Level)	ADF (1st Diff.)	PP (1st Diff.)	ZA Level t-Statistic	Break Year (Level)	ZA 1st Diff. t-Statistic	Break Year (FD)
ln(RET)	3.0155	3.4015	-5.1021***	-5.1997***	-3.768	2014	-7.929***	2010
ln(FD)	1.9580	3.0671	-4.9377***	-4.8957***	-4.686**	1998	-6.523***	2014
ln(EE)	0.1986	0.3511	-5.2905***	-5.7059***	-3.133	2014	-5.700***	2018
ln(CO_2)	-0.2286	0.2812	-4.2804***	-6.6500***	-5.200**	1997	-6.164***	1999
ln(GDPG)	-3.2450***	-3.1537***	—	—	-6.048***	2003	-8.935***	1996
ln(TR)	-1.0885	-0.5560	-4.7285***	-4.6637***	-3.121	2015	-6.882***	2009
ln(FDI)	-4.6413***	-4.7642***	—	—	-6.648***	2001	-9.972***	1999
ln(GOV)	-2.5048	-1.0502	-6.5142***	-6.6800***	-4.522**	2013	-7.158***	2016
ln(OILR)	-0.4448	-0.2740	-6.5588***	-6.5993***	-3.782	2018	-7.073***	2012
ln(HCI)	1.3381	8.3419	-1.0290	-1.0184	-3.187	2005	-3.393*	2001

Note: ***, **, and * denote significance levels at 1%, 5%, and 10%, respectively. The ADF and PP tests include intercept and trend specifications. The Zivot and Andrews [30] test accounts for one endogenous structural break in the series.

4.4. Cointegration test

As presented in Table 6, the results of the ARDL Bound Test for Cointegration seek to identify the existence of long-run equilibrium between the variables in the model. The test is based on Pesaran et al. [31] but is most appropriate for situations in which the series in the system are I (0) or I (1), but not I (2). In this case, the F-statistics estimates the joint significance of the regressors in the system in terms of explaining the response of the dependent variable in the long run.

The F-statistic value is 6.254, higher than the 5% upper bound of 4.35. This implies the rejection of the null hypothesis of no long-run relationship between the variables in the system; thus, there is evidence of cointegration between the variables in the system.

The existence of a long-run equilibrium implies that the major drivers of the energy transition in the country in the long run, such as FD, human capital, EE, government spending, foreign investments, among others, are related in the long run. Thus, in the short run, the system should be able to correct itself to move toward the long-run equilibrium path.

Table 6. ARDL bounds test for cointegration.

Test Statistic	F-Statistic	5% Lower Bound	5% Upper Bound	Decision
ARDL Bounds F	6.254	3.23	4.35	Cointegration exists

4.5. Long-run ARDL / FMOLS / DOLS results

Table 7 outlines the findings of the long-run ARDL, FMOLS, and DOLS estimators for the determinants of Renewable Energy Transition (RET). Overall, the results reveal significant long-run relationships between RET and several economic, financial, environmental, and institutional factors. The consistency of signs and significance levels across the three estimators strengthens the robustness and reliability of the empirical findings. The findings are discussed in relation to the empirical literature to identify areas of consistency and divergence and to explain the Saudi-specific economic and institutional context under Vision 2030 reforms.

Most importantly, the results reveal a strong and positive relationship between FD and renewable energy transition. FD, measured by ln(FD), positively affects RET in the ARDL and DOLS estimations, while FMOLS confirms a positive and significant effect, although with a smaller coefficient. This finding suggests that when the financial system is more developed, it makes it easier to obtain money for renewable energy projects while pushing private-sector involvement in sustainability-oriented investments, which is somewhat the bigger idea here. In Saudi Arabia, the financial sector reforms tied to Vision 2030, with green financing programs and sustainable investment tools, have helped in supporting the roll out of renewables. These results line up with work that has pointed to how FD can back the low-carbon shift processes [34,35].

The long-run estimates further show that EE, captured by ln(EE), has a positive and statistically significant effect on the renewable energy transition across the ARDL, FMOLS, and DOLS estimators. This points to how critical EE is for cutting energy wastage and for making it smoother to connect renewable technologies into the overall national energy setup, even when the system is under pressure.

The outcome fits with the environmental economics discussion where EE and renewable energy adoption are often seen as complementary rather than competing. [27,36].

On the contrary, CO_2 emissions, when they are expressed as ln(CO_2), show a negative and statistically significant association with RET across every estimator used. This output indicates that a stronger reliance on fossil fuels, along with greater carbon intensity, can slow the movement toward renewable energy sources. In a sense, the sign of the relationship aligns with earlier evidence, where it is noted that countries characterized by heavy fossil-fuel dependence often develop structural obstacles for a greener energy makeover [37,38].

For economic growth, proxied via ln(GDPG), the evidence feels mixed depending on which estimator is applied. The ARDL and DOLS specifications deliver a positive and significant effect, so economic expansion seems to generate more slack and motivations for renewable energy investments, as well as for technological upgrading. However, the FMOLS approach delivers rather small negative coefficient, which hints that economic growth may not push the renewable energy transition in a single direction everywhere because its effect could shift with economic structure, plus the general policy orientation.

TR, shown as ln(TR), also delivers mixed evidence. In the ARDL estimator, it comes out positive for the renewable energy transition, but when FMOLS and DOLS are used, they show negative coefficients. That pattern hints that higher trade openness could encourage fossil-fuel- intensive imports and in turn increase energy consumption. Thus, TR might yield positive and negative outcomes for the renewable energy transition depending on the trade-flow makeup [28,29].

FDI, written as ln(FDI), on the other hand, has a positive and statistically significant connection with the renewable energy transition in every estimator. FDI helps the transition through technology spillovers, managerial know-how, and extra financing for renewable infrastructure. The DOLS coefficient is also relatively larger, so it seems the positive effect of foreign investment may strengthen, more gradually, with time. This lines up with studies that treat FDI as an important driver for green technology diffusion and for a cleaner energy pathway [39,40].

GOV, when measured as ln(GOV), also turns up as positive and statistically significant across all models, though the exact size is not identical from one specification to the next. This kind of outcome supports the central role of public spending, institutional reinforcement, and government policy initiatives for steering capital toward renewable energy projects and wider sustainable development themes. The relatively high DOLS coefficient, in particular, hints that public interference may bring about effects that last for a long while in terms of renewable energy growth [41].

Concerning oil rents, which I proxy with ln(OILR), the ARDL estimator suggests a negative relationship with the renewable energy transition; this matches the resource curse story where heavy reliance on fossil fuels could dampen the green move. Furthermore, FMOLS and DOLS give those small positive coefficients, so it may be the case that oil revenues also provide some kind of short run fiscal breathing room that can be steered toward renewable investment. Thus, the overall picture is a bit mixed, though still readable, and oil rents might encourage and delay the transition depending on how policy decisions are budgeted and whether real diversification efforts are in place [42,43].

Finally, human capital, noted as ln(HCI), turns out positive and statistically significant across every estimator. This indicates that schooling, practical expertise, and the innovation capacity they nurture help with adoption, management, and diffusion of renewable energy technologies. The bigger

coefficients coming from FMOLS and DOLS, when viewed together, strengthens the idea that human capital is not just helpful but required for the long run renewable energy transition and even broader sustainable economic change.

Table 7. Comparison of long-run estimators (ARDL, FMOLS, and DOLS).

Variables	ARDL	FMOLS	DOLS
ln(FD)	0.426***	0.023**	0.268***
ln(EE)	0.304***	0.095**	0.130**
ln(CO2)	-0.146**	-0.136**	-0.381**
ln(GDPG)	0.027**	-0.011**	0.125**
ln(TR)	0.149**	-0.210***	-0.704**
ln(FDI)	0.012**	0.007**	0.268***
ln(GOV)	0.456**	0.172**	0.545**
ln(OILR)	-0.112**	0.052*	0.154**
ln(HCI)	0.797***	0.730***	0.863***

Note: ***, **, and * denote significance at 1%, 5%, and 10%, respectively.

4.6. ECM Short-run dynamics

Table 8 shows the short run dynamics of the ECM that is estimated in the ARDL framework for renewable energy transition (RET) and is meant to capture how things adjust over time. The coefficient of the error correction term, ECT (−1), comes out negatively and is statistically significant at the 5% level. This points to a stable long-run equilibrium link among the variables. The estimated value of −0.4874 suggests that around 48.7% of the short-run disequilibrium gets corrected each year, moving back toward the long-run equilibrium path. Thus, the evidence hints at a relatively quick pace of adjustment after short-term shocks.

On the short-run side, FD, shown as Δln(FD), has a negative effect, but it is only weakly significant, at the 10% significance level. In other words, short-term swings in FD may temporarily curb renewable energy transition. A plausible interpretation is that there are adjustment costs or a kind of delayed financial allocation process, which slows renewable energy investments until things settle.

Renewable energy transition has been positively influenced by increased efficiency of energy use (Δln(EE). The data shows that improving efficiency in energy use is reflective of better utilization of resources and reducing waste in terms of energy.

In the short term, an increase in carbon emissions (Δln(CO_2)) is very statistically significant in relation to an increase in the rate of transition to renewable energy. This is potentially due to the increased pressure on the speed of adopting clean energy and developing environmental policy to combat the rates at which the environment is degrading.

Newly increased economic growth, as represented by Δln(GDPG), affects the short-term success of the renewable energy transition with a positive (significant) effect. That is, as the economy grows, more resources will be available for financing projects, investing in technological advancements, and developing infrastructure to speed up the processes around the development of renewable energy.

Similarly, openness to trade (Δln(TR)) and acceptance of imports (Δln(FDI)) will positively affect the renewable energy transition. This means that increasing integration into the global trade market and bringing in FDI help advance the process of renewed energy systems by facilitating technology transfers, providing access to renewable technologies, and providing financial capital to invest in new technologies.

The role of public spending and support for renewable energy infrastructure and sustainable development initiatives is reflected in the positive and significant GOV coefficient (Δln(GOV)). Although oil resource rents (Δln(OILR)) have a small positive but significant effect on financing renewable energy and diversification policies, they are likely to provide only temporary support to these efforts. Conversely, human capital (Δln(HCI)) has a significant negative coefficient, indicating that there may persist, in Saudi Arabia, structural rigidities or mismatches regarding the skills of workers, and that there is a lag in converting improvements in human capital into tangible outcomes immediately related to renewable energy development. The overall results from the ECM models indicate that a long-run equilibrium exists between renewable energy transition and its major economic, environmental, and institutional determinants, and that an active existence of dynamic short-run relationships provides additional support for this conclusion.

Table 8. Short-run ECM results.

Variable	Coefficient	Std. Error (corrected)	t-Statistic (corrected)	*P*-value
ECT(−1)	-0.4874	0.1780	-2.74	0.012**
Δln(FD)	−0.0094	0.0056	−1.69	0.090*
Δln(EE)	0.0563	0.0261	2.16	0.031**
Δln(CO2)	0.0663	0.0240	2.76	0.006***
Δln(GDPG)	0.0075	0.0024	3.09	0.002***
Δln(TR)	0.0239	0.0127	1.88	0.060*
Δln(FDI)	0.0128	0.0055	2.33	0.020**
Δln(GOV)	0.1229	0.0511	2.41	0.016**
Δln(OILR)	0.0113	0.0062	1.83	0.067*
Δln(HCI)	−1.3458	0.5576	−2.41	0.016**
Constant	3.5809	1.5005	2.39	0.027**

Note: *, **, and *** represent significance at the 10%, 5%, and 1% levels, respectively.

5. Conclusion and policy implications

The relationship between sustainable development, renewable energy transition, and finance in Saudi Arabia has been analyzed using the ARDL, FMOLS, and DOLS methodologies, covering 1990 through 2024. The findings show that the three variables are in long-run equilibrium and that both financial matters, and environmental and institutional factors help explain the transition to renewable energy within Saudi Arabia.

The results show that financial advancement is important because it contributes to the transition to renewable sources of energy by providing access to money, reducing the constraints on liquidity for projects, and contributing to investments into green energy. The results also show that EE and human

capital improve the adoption of renewable energy sources. Therefore, technological ability and skilled labor supply will contribute to supporting the transition toward renewable energy. However, CO2 emissions consistently exert a negative impact on the transition toward renewable energy. This indicates that increased levels of environmental degradation represent a continuing structural barrier to sustainable transformation of the energy sector.

However, the effects of TR vary greatly by the estimating procedure, indicating that there is some degree of heterogeneity across estimates, and that this effect will vary with whether the trade channel is driven by clean sources or alternative energy sources. Similarly, oil rent effects also vary between the models, giving further evidence to support oil resource revenues that have a dual-use role, and while they will continue to support the development of fossil fuels, they may also provide the funding necessary to redirect into investment toward renewable energy where appropriate policies are implemented to do so. The mixed findings from the results demonstrate the complexity of the energy transition process in rich resource economies.

At the macro level, this evidence supports the assertion that renewable energy transition is a necessary environmental step and represents an essential driver for long-term economic diversification and sustainability. The results are consistent with the goals of the Vision 2030 Framework of Saudi Arabia, which focuses on reducing its reliance on oil, building up economic resilience, and fostering green growth.

The empirical data suggests that policymakers should implement an integrated policy model that combines financial, energy, and environmental reforms. Developing green finance tools (green sukuk, climate bonds, and sustainable investment funds) will help leverage private capital for renewable energy projects. In addition, enhancing the level of environmental risk disclosure and improving ESG reporting standards will improve the transparency of the market, thereby encouraging sustainable investment practices.

To help speed up the increase in technology adoption, public investment should focus on the renewable energy infrastructure, research and development, and human capital formation (human capital). In addition, strengthening public–private partnerships will be critical in scaling up large renewable energy projects, such as those found under the Saudi Green Initiative.

In addition to public investments toward renewable energy projects, gradually reforming fossil fuel subsidies with accompanying targeted fiscal incentives for renewable energy companies would also help re-allocate resources toward the clean energy sector. Institutional strengthening and regulatory stability are also essential to ensure the successful execution of long-term energy transition policies.

There are some limitations to the study though it does contribute to the knowledge base. For instance, using annual aggregate data may have hidden differences in sectors/regions within the Saudi economy. Furthermore, complex/nonlinear relationships among the variables were not accounted for in this model. Additionally, FD and human capital may be multicollinear and can therefore compromise the accuracy of coefficients, although some robustness checks were conducted.

Researchers may build upon this research by investigating sector-specific or regional data to better understand the dynamic of the transition to renewable energy. Researchers could also use nonlinear, asymmetric, or threshold models (e.g., NARDL or quantile regression) to analyze the degree of structural change. Comparative analysis of the findings across GCC countries and/or oil-dependent

economies may lead to greater generalizability of the findings. Finally, researchers may include indicators for innovation, institutional quality, and climate risk to enhance their analyses.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The author declares no conflict of interest.

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