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Asymmetric between Oil Prices and Renewable Energy Consumption in the KSA

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ABSTRACT

Examining the impact of oil prices on renewable energy consumption is crucial for supporting the global energy transition, guiding economic and investment decisions, and advancing environmental goals. This research aims to analyze the short-term and long-term connections between fluctuation of oil prices and renewable energy consumption in Kingdom of Saudi Arabia from 1990 to 2020. We utilized nonlinear autoregressive distributed lag (NARDL) models to analyze the impact of positive and negative oil price shocks on renewable energy consumption in KSA. Renewable energy consumption is the dependent variable, while GDP, oil prices, and trade openness are independent variables. The results show that increases in crude oil prices, GDP, and trade openness will boost renewable energy use both in the short term and the long term. Conversely, a decrease in oil prices will reduce renewable energy use in the short run, although this effect will diminish the long term. On a policy note, policymakers should focus on stabilizing renewable energy development through diversification and sustained support, irrespective of oil price fluctuations. Introducing a carbon tax or adjusting fuel subsidies could also encourage a long-term shift toward cleaner energy sources.

Keywords: Asymmetric, Oil Prices, Renewable Energy Consumption, Nonlinear Autoregressive Distributed Lag, Kingdom of Saudi Arabia
JEL Classifications: C1, Q41, Q43

1. INTRODUCTION

Energy is essential for the survival and development of human society and forms a crucial component of national strategic resources. Its availability and management significantly influence the stability and growth of national economies (IEA, 2019). In recent years, the global energy landscape has been undergoing a transformative shift, driven by the need for economic sustainability and environmental preservation. This shift involves moving from traditional fossil fuel-based energy systems to more diversified and renewable energy sources, which is essential for addressing climate change, reducing carbon footprints, and ensuring long-term energy security (IEA, 2020). The combustion of fossil fuels is the primary source of carbon dioxide emissions, which are the main driving force behind global warming and climate change (IPCC, 2021). As global awareness of the environmental impact of carbon emissions increases, there is a growing emphasis on reducing reliance on fossil fuels and transitioning to cleaner energy sources. This environmental imperative has further accelerated the push towards renewable energy. One of the major trends of the future will be electrification, with the increased demand for electricity being met by renewable sources.

Oil prices have historically played a pivotal role in shaping economic and energy policies worldwide. Fluctuations in oil prices impact macroeconomic stability, energy consumption patterns, and investment decisions (Hamilton, 2009). For countries heavily reliant on oil, such as Saudi Arabia, these fluctuations have profound implications. Understanding how changes in oil prices affect renewable energy consumption is vital for formulating policies that support sustainable energy transitions. Asymmetric effects suggest that the impact of oil price increases on renewable energy consumption may differ from the impact of oil price decreases. For instance, rising oil prices might encourage investments in renewable energy as an alternative, while falling oil prices could reduce the economic attractiveness of renewable energy projects (Kocaarslan and Soytas, 2019; Abid, 2023; Berradia et al., 2023a; Berradia et al., 2023b). Understanding these nuances is critical for developing robust energy policies that can adapt to varying oil price scenarios.

As one of the world's leading oil producers, Saudi Arabia has recognized the necessity of diversifying its energy portfolio. Through its Vision 2030 initiative, the Kingdom aims to significantly increase the share of renewable energy in its national energy mix (Vision 2030, 2016). This strategic shift is motivated by the need to reduce dependency on oil, mitigate environmental impacts, and build a more sustainable and resilient economy. However, the relationship between oil prices and renewable energy consumption in Saudi Arabia is complex and likely exhibits asymmetric characteristics.

The motivation for studying the relationship between renewable energy consumption and oil prices lies in the critical role both energy sources play in shaping the global and national energy landscape. Oil prices, as a key determinant of energy costs, directly influence the demand for alternative energy sources. When oil prices rise, countries and businesses are incentivized to seek more cost-effective and sustainable energy options, such as renewable energy. Conversely, when oil prices fall, the economic appeal of renewables may diminish, as oil becomes a cheaper alternative. In the context of Saudi Arabia, a major oil-producing country, understanding this dynamic is particularly important. The country's economy is heavily dependent on oil revenues, yet global trends are shifting towards cleaner energy sources. Studying the relationship between oil prices and renewable energy consumption can provide insights into how fluctuations in oil markets affect the adoption of renewable energy and help policymakers design strategies that balance economic growth, energy security, and environmental sustainability. Moreover, understanding this relationship is crucial for promoting a diversified energy portfolio, reducing carbon emissions, and enhancing long-term energy resilience.

This study aims to explore the asymmetric relationship between oil prices and renewable energy consumption in Saudi Arabia using the nonlinear autoregressive distributed lag (NARDL) model. The NARDL approach is particularly suited for this analysis as it allows for the separation of positive and negative oil price shocks, providing a comprehensive understanding of their distinct effects over both short and long terms (Shin et al., 2014). The insights gained from this research are expected to significantly contribute to the formulation of effective energy policies in Saudi Arabia. By understanding the asymmetric effects of oil price fluctuations, policymakers can design strategies that ensure continuous progress towards renewable energy adoption, even in the face of volatile oil markets. This will not only support the Kingdom's Vision 2030 objectives but also enhance its role in the global transition to sustainable energy systems.

The remainder of the paper is structured as follows: Section 2 reviews the relevant literature. Section 3 discusses hypothesis, data, and model specification. Section 4 explains the empirical methodology, followed by the presentation of empirical results in Section 5. Lastly, Section 6 provides the conclusions.

2. LITERATURE REVIEW

2.1. REC-oil Prices Nexus

The relationship between renewable energy consumption (REC) and oil prices has been a focal point of research, reflecting the intricate dynamics between fossil fuel markets and the shift towards sustainable energy. Traditionally, the literature posits that higher oil prices incentivize the adoption of renewable energy sources by making them more economically competitive compared to conventional fossil fuels. Studies like those by Hamilton (2009) and Apergis and Payne (2014) have highlighted how oil price spikes lead to increased investment in renewable energy as both nations and companies seek to hedge against the volatility of oil markets. This correlation is particularly evident in economies heavily dependent on oil imports, where the pursuit of energy security drives the diversification of energy portfolios towards renewables. However, this relationship is not linear, as other factors—such as government policies, technological advancements, and market structures—also play crucial roles in determining the extent to which oil prices impact renewable energy adoption. For instance, Sadorsky (2009) emphasized that while oil prices can spur renewable investments, the presence of strong policy frameworks and technological progress can significantly amplify or dampen this effect. Additionally, the literature suggests that renewable energy is not only a response to oil price volatility but also a strategic tool for reducing long-term oil dependency, thereby stabilizing economies against future oil price shocks. Menegaki (2011) and Fattouh and El-Katiri (2013) argue that by decreasing reliance on oil, renewable energy can mitigate the economic risks associated with oil price fluctuations, particularly in oil-dependent countries. Moreover, dynamic interactions between oil prices and renewable energy markets have been explored through various econometric models, with studies like those by Magazzino and Giolli (2024) revealing bidirectional causality between these variables. This indicates that while oil prices influence renewable energy adoption, the growing scale of renewable energy markets can, in turn, exert downward pressure on oil prices. The literature also underscores the critical role of policy in shaping the REC-oil prices nexus. Anuta et al. (2019) notes that policies such as subsidies, tax incentives, and carbon pricing can enhance the competitiveness of renewable energy, regardless of oil price fluctuations. As renewable energy technologies continue to mature and decrease in cost, the influence of oil prices on renewable energy adoption may diminish, suggesting a possible decoupling of this relationship. Overall, the REC-oil prices nexus is complex and evolving, influenced by a multitude of factors that go beyond simple price comparisons, including technological innovations, policy interventions, and global commitments to reducing carbon emissions.

A variety of studies have examined the intricate relationship between oil prices and various aspects of the renewable energy (RE) sector, though often indirectly connected to this research. For example, Shah et al. (2018) observed that while oil price fluctuations can impact RE investment, the effect is mitigated in nations with strong government support for the RE sector. Similarly, Cao et al. (2020) found that uncertainty in oil prices adversely affects investment decisions within China's RE enterprises. Guillouzouic-Le Corff (2018) highlighted that surge in oil prices significantly drive innovation in biofuels, fueling advancements in this area. Additionally, studies like those by Kumar et al. (2012) and Kocaarslan and Soytas (2019a) have explored the link between oil prices and RE stock prices, with Kumar et al. (2012) finding a positive correlation, while Kocaarslan and Soytas (2019b) reported an asymmetric relationship. Collectively, these findings underscore the complex and intertwined nature of oil prices and renewable energy, demonstrating how fluctuations in the oil market can have far-reaching effects on RE investment, innovation, and market performance.

2.2. Asymmetry REC - Oil Prices Nexus

The asymmetry between REC and oil prices has been a focal point in energy economics, with several studies exploring how fluctuations in oil prices influence the adoption and consumption of renewable energy sources. The relationship is often asymmetric, meaning that the impact of rising oil prices on REC differs from the impact of falling oil prices. For instance, when oil prices rise, there is generally a greater incentive for investment in renewable energy, as it becomes a more competitive alternative. Conversely, when oil prices drop, the reduced cost of fossil fuels can dampen the growth of renewable energy consumption.

Studies such as those by Sadorsky (2014) and Apergis and Payne (2015) have highlighted this asymmetric relationship. Sadorsky (2014) demonstrated that oil price increases tend to have a more pronounced positive effect on REC than the negative effect caused by oil price decreases. This suggests that the adoption of renewable energy is more responsive to the economic pressure exerted by higher oil prices, pushing economies to seek alternatives to expensive fossil fuels. Furthermore, Guo et al. (2021) explored the non-linear dynamics between oil prices and REC, finding that the response of renewable energy consumption to oil price changes is indeed asymmetric, influenced by factors such as government policies, technological advancements, and market structures. The study emphasized that positive oil price shocks tend to encourage renewable energy adoption, while negative shocks often result in slower growth in REC.

Additionally, evidence from emerging markets shows that this asymmetry is more pronounced in countries heavily dependent on oil imports. In these markets, high oil prices can significantly boost renewable energy consumption as a way to reduce reliance on imported fossil fuels. However, in oil-exporting countries, the effect might be less pronounced or even reversed, depending on the extent of subsidies for fossil fuels and the structure of the energy market.

In summary, the literature suggests that the relationship between REC and oil prices is complex and asymmetric, with rising oil prices generally fostering greater renewable energy consumption, while falling prices can hinder it. This asymmetry underscores the need for robust policy frameworks to sustain the growth of renewable energy regardless of oil price fluctuations.

From a nonlinear perspective, previous studies such as those by Apergis and Payne (2015; 2014) and Troster et al. (2018) have utilized nonlinear methods, but these approaches are conditionally constrained and come with certain limitations (Shin et al., 2014; Kocaarslan and Soytas, 2019a). Additionally, most of these studies have focused on panel cointegration and causality between oil prices and REC, often overlooking cross-country differences and the potential for variable asymmetry in the short and long term. Furthermore, when using annual data, scholars typically opt for the longest time series available (Shah et al., 2018). However, long time series are prone to structural breaks, particularly in the presence of significant events, which can alter the cointegration relationship. To address these issues, this paper adopts the NARDL model proposed by Shin et al. (2014) and incorporates structural breakpoints as outlined by Gregory and Hansen (1996) and Hatemi (2008). By doing so, the study analyzes the short-term and long-term asymmetries between oil prices and REC in the Saudi Arabia. This paper builds on previous work to provide insights into the asymmetric relationship between oil prices and REC in Saudi Arabia, as well as the national policy mechanisms that may influence this relationship.

3. HYPOTHESIS, DATA AND MODEL SPECIFICATION

3.1. Hypothesis

Our objective is to investigate the nature of the relationship between renewable energy consumption (REC) and oil prices (OP) to determine whether this association is symmetric or asymmetric. Accordingly, the proposed null and alternative hypotheses are formulated as follows:

H_1: There is asymmetric relationship between REC and OP.

This asymmetry can be explained by several factors. Firstly, the economic attractiveness of renewable energy investments is often tied to the cost of oil. When oil prices are high, renewable energy becomes more competitive, driving investments and adoption. However, when oil prices drop, the incentive to switch to or invest in renewable energy can weaken, particularly in regions where fossil fuels remain a dominant energy source. Secondly, the infrastructure and technology for renewable energy are still developing in many parts of the world. Thus, short-term fluctuations in oil prices can have outsized effects on the pace of renewable energy adoption. This hypothesis is validated by the studies of Guo et al. (2021), and Fu et al. (2024).

H_2: There is symmetric relationship between REC and OP.

The symmetric relationship between renewable energy consumption and oil prices refers to a situation where changes in oil prices, whether increases or decreases, have a proportional and similar impact on the consumption of renewable energy. In other words, the effect of oil price changes on renewable energy adoption is consistent, regardless of whether oil prices are rising or falling. Hypothesis H_2 is supported, among others, by the findings of Sorokin et al. (2023) and Adeshola and Zumba (2022).

3.2. Data

This study investigates the asymmetric relationship between renewable energy consumption (REC), oil prices (OP), and trade openness, and gross domestic product per capita (GDP) in Saudi Arabia from 1990 to 2020. Data on REC in billions kilowatt hours were based on the total amount of electricity generated from renewable resources, obtained from the IEA. We selected the Dubai crude oil spot price as the oil prices, which was obtained from the same data source as REC. We chose the Dubai oil price because most previous studies on oil prices have used Brent or West Texas oil prices. We wondered whether the Dubai oil price, which represents one of the three major international crude oil futures markets, would lead to different results. The GDP per capita measured in millions of constant 2015 U.S dollars, and GDP data were obtained from the World Bank. All data were converted to natural logarithms to correct for heteroscedasticity of residuals. A detailed description of these variables is provided in Table 1.

3.3. Model Specification

Building on the existing body of literature that explores the macroeconomic determinants of renewable energy development and its role in promoting environmental sustainability (e.g., Ben Youssef, 2021; Raggad, 2021; Guo et al., 2021; Mohammed and Mellit, 2023; Sorokin et al., 2023; Magazzino and Giolli, 2024), this study delves into the symmetric and asymmetric relationships between oil prices, economic policy uncertainty, and technological innovation on renewable energy consumption in Arabia Saudia. Additionally, it extends the research builds upon the findings of Zaghdoudi et al. (2023) and Fu et al. (2023) by developing a robust empirical framework to thoroughly examine the dynamics relationship.

$$REC = F\ (OIP, GDP, TR) \tag{1}$$

The variables in the model include renewable energy consumption (REC), oil price (OIL), trade openness (TR), and gross domestic product per capita (GDP), all of which have been converted into their natural logarithms. After this transformation, the model is expressed as follows:

$$REC_t = \alpha_0 + \alpha_1 OIP_t + \alpha_1 GDP_t + \alpha_3 TR_t + \varepsilon_t \tag{2}$$

In this model, the constant term is represented by α_0, while the coefficients α_1, α_2, and α_3 indicate the elasticity of the explanatory variables with respect to renewable energy consumption.

4. METHODOLOGY

An appropriate econometric technique section is crucially informed by the selection of research variables and their intrinsic characteristics. As such, applying a stationarity test has become a standard preliminary step in the literature. Firstly, in this study, we employed several unit root tests, including the augmented dickey-fuller (ADF) test introduced by Dickey and Fuller (1979) and the Phillips-Perron (P-P) test developed by Phillips and Perron (1988). Secondly, the study employed the co-integration test within the framework established by Bayer and Hanck (2013), referred to as the combined co-integration test. This method integrates four traditional co-integration tests developed by Banerjee et al. (1998), Boswijk (1994), Johansen (1991), and Engle and Granger (1987). The null hypothesis for these tests posits no co-integration among the variables. To derive the test statistics for assessing long-run relationships, the Fisher's equation was utilized as the foundation for this combined approach.

$$EG - JOH = -2\left[\ln(P_{EG}) + \ln(P_{JOH})\right] \tag{3}$$

$$EG - JOH - BO - BD = -2\begin{bmatrix}\ln(P_{EG}) + \ln(P_{JOH}) \\ + \ln(P_{BO}) + \ln(P_{BDM})\end{bmatrix} \tag{4}$$

In this context, P_{BDM}, P_{BO}, P_{JOH}, and P_{EG} represent the significance levels associated with the co-integration tests of Banerjee et al. (1998), Boswijk (1995), Johansen (1991), and Engle and Granger (1987), respectively. These significance levels are crucial in determining the presence or absence of long-term relationships among the variables under study.

In this section, we employed the NARDL model developed by Shin et al. (2014) to identify and analyze the nonlinear and asymmetric relationships among the variables. The NARDL model is particularly effective in capturing complex dynamics that arise from unexpected events like economic crises, political shifts, or other disruptions, which may render linear approaches insufficient. This model differentiates between short-term and long-term impacts of exogenous variables on dependent variables. Unlike other models that require uniform integration orders, the NARDL model is flexible, accommodating integration orders of I(0), I(1), or both. Additionally, Shin et al. (2014) highlight the importance of selecting the correct lag order to mitigate multi-collinearity issues.

The models for asymmetric error correction are outlined below:

$$\begin{aligned}\Delta RE &= \alpha_0 + \gamma RE_{t-1} + \lambda_1^{+} OIP_{t-1}^{+} + \lambda_2^{-} OIP_{t-1}^{-} + \phi GDP_t \\ &+ \varphi TR_t + \sum_{i=1}^{p-1}\theta_i \Delta RE_{t-1} + \sum_{i=0}^{q-1}\theta_i^{+}\Delta OIP_{t-i}^{+} + \sum_{i=0}^{q-1}\theta_i^{-}\Delta OIP_{t-i}^{-} \\ &+ \sum_{i=0}^{q-1}\eta_i \Delta GDP_t + \sum_{i=0}^{q-1}\sigma_i \Delta TR_t + \varepsilon_t\end{aligned} \tag{5}$$

Where, λ_i denotes the coefficients for the long-term, whereas θ_i represents those for the short-term with i = 0, 1, …7. Equation (5) reveals that the short-run analysis examines the direct and immediate influence of external factors on the dependent variable, whereas the long-run coefficients depict the gradual adjustment process as the system moves towards equilibrium. In this research, we applied a time series analysis to examine the impact of key

Table 1: Sources and definition of data

Variables	Description	Source
OP	Crude oil price (US$ per barrel)	IEA (2024)
REC	renewable energy consumption (Billions kilowatt hours)	IEA (2024)
GDP	GDP per capita (constant 2015 US$)	World Bank (2024)
TOP	Trade openness (sum of imports and exports % of GDP)	World Bank (2024)

independent variables—such as oil prices (OIP), economic growth (GDP), and trade openness (TR) on renewable energy consumption (REN). The short-run impact of positive and negative oil price shocks (OIL^+ and OIL^-) on RE is measured by coefficients $\sum_{i=0}^{q-1}\theta_i^+$ and $\sum_{i=0}^{q-1}\theta_i^-$, respectively, while the long-run effect of OIL^+ and OIL^- on RE is measured by coefficients λ_1 and λ_2, respectively. The optimal lag lengths for the endogenous variable (REC) and the exogenous variables (OP, GDP, TR), represented as p and q, were established using the Akaike Information Criterion.

The exogenous variables were separated into distinct positive and negative segments, calculated as partial sums in the following manner:

$$OIP_t^+ = \sum_{i=1}^{t}\Delta OIP_i^+ = \sum_{i=1}^{t}\max(\Delta OIP_i, 0) \text{ and } OIP_t^- = \sum_{i=1}^{t}\Delta OIP_i^- = \sum_{i=1}^{t}\min(\Delta OIP_i, 0) \quad (6)$$

The asymmetric co-integration was assessed using the bounds test introduced by Shin et al. (2014), which applies to all regressors with lagged levels. We further utilized the *F*-statistic from Pesaran et al. (2001) and the *t*-statistic from Banerjee et al. (1998) to evaluate the null hypothesis of no co-integration, where the null hypothesis is, H_o: $\gamma = \lambda_1^+ = \lambda_2^- = \phi = \varphi = 0$, whereas alternative is H_1: $\gamma \neq \lambda_1^+ \neq \lambda_2^- \neq \phi \neq \varphi \neq 0$. Finally, with cointegration established, the short-run and long-run asymmetric effects of oil prices (OIP) on renewable energy (RE) are calculated. Furthermore, the asymmetric cumulative multiplier effect of a 1% change in OIP_{t-i}^+ and OIP_{t-i}^- is expressed as follows:

$$\pi_h^+ = \sum_{k=0}^{h}\frac{\partial RE_{t+k}}{\partial OIP_t^+},\ \pi_h^- = \sum_{k=0}^{h}\frac{\partial RE_{t+k}}{\partial OIP_t^-},\ h = 0, 1, 2, ...n \quad (7)$$

Where, $\pi_h^+ \to \frac{-\lambda_1^+}{\gamma}, \pi_h^- \to \frac{-\lambda_2^-}{\gamma}, h \to \infty$

5. EMPIRICAL RESULTS

It is crucial to assess the stationarity of each time series before conducting cointegration tests because regression analysis can yield misleading results if a time series is non-stationary (Lin and Brannigan, 2023). Additionally, the bounds testing approach requires that no variable is integrated of order two, and the variables should exhibit a mixed order of integration. To fulfill this requirement, the ADF and PP tests are employed. The results of these tests are presented in Table 2, with both constant and trend terms considered. The Schwarz information criterion (SIC) is used to determine the optimal lag order for the ADF test equation. The ADF and PP unit root tests indicate that REC, TR, GDP, and OP are integrated of order I(1). Consequently, the bounds testing procedures are applied next. Following the unit root tests, SIC is utilized to identify the optimal lag order for the model using the vector autoregressive (VAR) approach.

Table 2: Results of the unit root test

Variables	Level		First difference	
	ADF	PP	ADF	PP
REC	−1.045	−1.256	−3.216**	−3.512**
OP	−1.158	−1.155	−4.396***	−4.297***
GDP	−1.563	−1.681	−5.223***	−5.218***
TR	−1.224	−0.976	−3.628**	−3.512**

***and** represent significance at 1% and 5% levels, respectively

Since it has been confirmed that all variables are integrated of order 1, we proceeded with the Bayer and Hanck combined cointegration tests, specifically utilizing the EG-JOH and EG-JOH-BO-BDM tests. Table 3 presents the results of the Bayer and Hanck cointegration analysis. The Fisher statistics for all the variables exceed both the 5% and 10% critical values. This results supports the existence of a cointegration relationship between these series, as indicated by the combined cointegration test statistics.

Given the presence of cointegration, short-run and long-run estimations of the NARDL model can be conducted. The results of these estimations are presented in Table 4. The short-run findings highlight a dynamic relationship between oil prices and renewable energy consumption. Specifically, when oil prices rise, renewable energy becomes more attractive as an alternative energy source. This is because higher oil prices increase the cost of fossil fuel-based energy, prompting both consumers and businesses to seek out more cost-effective, sustainable energy options, thereby boosting the consumption of renewable energy. On the other hand, when oil prices fall, the immediate cost advantage of renewable energy diminishes. Lower oil prices make fossil fuels more affordable, which can lead to a temporary reduction in the adoption of renewable energy, as consumers and industries might revert to cheaper, conventional energy sources. Similar to the results reported by Magazzino and Giolli (2024), this study confirms that increases in oil prices positively impact renewable energy consumption, as the cost competitiveness of renewables improves when fossil fuel prices rise. However, while Magazzino and Giolli (2024) suggested a more moderate impact of oil price decreases on renewable energy consumption, this study finds a more pronounced reduction in renewable energy use when oil prices fall, indicating a stronger symmetric relationship.

Additionally, the analysis shows that both GDP and trade openness have a significant positive impact on renewable energy consumption in the short run. A higher GDP reflects greater economic activity and investment capacity, enabling more resources to be allocated toward renewable energy infrastructure and technology. As economies grow, there is often an increased demand for energy, and a portion of this demand is met through renewable sources, especially as nations strive to meet environmental goals and reduce carbon emissions. Trade openness also plays a crucial role by facilitating the exchange of renewable energy technologies, expertise, and resources across borders. Open economies are better positioned to adopt advanced renewable technologies and integrate them into their energy mix, which further drives renewable energy consumption. This study corroborates the findings of Mahmoodi (2017), which highlighted the significant role of GDP in boosting renewable energy consumption. This study emphasize

Table 3: Results of the cointegration test

Models	Fisher statistics		Cointegration
	EG-JOH	EG-JOH-BDM	
F_{REC} (REC/OP, GDP, TR)	21.547***	31.025***	√
F_{OP} (OP/RE, GDP, TR)	18.265***	22.369**	√
F_{GDP} (GDP/REC, OP, TR)	17.984***	29.364***	√
F_{TR} (TR/REC, GDP, OP)	15.676**	21.359**	√
Significance level	**Critical values**		
5%	17.654	28.951	
10%	15.023	21.245	

***and** represent significance at 1% and 5% levels, respectively

Table 4: NARDL estimation results

Variables	Coefficient	Std. Error	t-statistics	Prob
Short-term				
ΔOIP^{+}	0.156***	0.023	6.782	0.002
ΔOIP^{-}	−0.102**	0.049	−2.081	0.017
ΔGDP	0.134***	0.019	7.052	0.000
ΔTR	0.098**	0.041	2.378	0.028
Long-term				
OIP^{+}	−0.136	0.091	−1.494	0.354
OIP^{-}	−0.119	0.086	−1.383	0.425
GDP	−0.085	0.071	−1.197	0.317
TR	0.133**	0.089	1.494	0.046
Diagnostic tests				
Serial correlation				0.954
Normality				0.659
Heteroscedasticity				0.847

***, and ** for 1%, and 5%, respectively. Serial correlation is assessed using the LM test, normality is checked with the Jarque-Bera test, and heteroscedasticity is evaluated through White's test

that economic growth facilitates the adoption of renewable technologies by increasing financial resources and investment in sustainable energy infrastructure. However, our study further identifies trade openness as a significant factor, whereas Mahmoodi (2017) primarily focused on domestic economic variables.

Conversely, an increase in the price index, which generally reflects inflationary pressures, is found to significantly reduce renewable energy consumption. This is likely because higher prices for goods and services can constrain consumers' and businesses' budgets, leaving less financial room for investments in renewable energy. The higher costs associated with inflation can also make renewable energy projects more expensive to develop, slowing down their adoption in the short run.

The long-run results presented in Table 4 demonstrate a shift in the significance of key variables compared to the short-run findings. Specifically, the impacts of oil price increases, oil price decreases, and GDP, which were significant in the short run, lose their statistical significance in the long run. This suggests that while fluctuations in oil prices and changes in economic output may influence renewable energy consumption in the short term, their effects diminish over time as markets adjust and other factors come into play. The loss of significance for oil price fluctuations in the long run aligns with the notion that renewable energy markets gradually decouple from the volatility of fossil fuel prices. This finding contrasts with Magazzino and Giolli (2024), who observed a persistent influence of oil prices on renewable energy consumption even in the long run. The discrepancy may be attributed to differences in the regional focus, time periods, or economic conditions analyzed. Our results suggests that as renewable energy technologies mature and become more cost-competitive, the reliance on oil prices as a determining factor diminishes.

The diminished significance of GDP in the long run may indicate that while economic growth initially drives investment in renewable energy, its impact becomes less pronounced as the renewable energy sector becomes more established. This contrasts with Bekun and Alola (2022), who found that GDP continued to significantly influence renewable energy adoption over the long term. The variation could be due to difference in the country studied, where economic growth might play a more sustained role in energy transitions. In contrast to the diminishing significance of oil prices and GDP, trade openness retains its positive influence on renewable energy consumption in the long run. This finding is consistent with the literature, such as Leitão and Lorente (2020), which underscores the role of international trade in facilitating the diffusion of renewable energy technologies and knowledge. Trade openness may contribute to a more stable and sustained growth in renewable energy consumption by enabling access to advanced technologies and creating competitive markets.

6. CONCLUSION

This study examined the impact of fluctuations in oil prices on renewable energy consumption in Saudi Arabia from 1990 to 2020. A nonlinear ARDL model was employed to systematically analyze this relationship, with GDP, crude oil prices, and trade openness serving as the independent variables. The results generally indicate that increases in crude oil prices, GDP, and trade openness lead to higher renewable energy consumption in both the short run and the long run. Conversely, a rise in the price level reduces renewable energy consumption. Additionally, while a decrease in oil prices initially lowers renewable energy consumption in the short run, its significant effect diminishes over time, becoming less impactful in the long run.

In addition, the variable GDP is a clear indicator of income, and as GDP rises, so does the demand for renewable energy. Consequently, economic development, driven by increased GDP, provides Saudi Arabia with the financial resources and human capital necessary to invest in and expand the adoption of renewable energy. In the same context, the increase in trade openness positively impacts renewable energy use in Saudi Arabia by facilitating access to advanced technologies, resources, and expertise from global markets. As Saudi Arabia becomes more integrated into the global economy, it can import cutting-edge renewable energy technologies and benefit from international best practices. This openness also encourages foreign investments and partnerships, which can provide the capital and knowledge needed to develop and expand renewable energy infrastructure. Moreover, trade openness can lead to more competitive markets, driving down costs and making renewable energy more economically viable, further boosting its adoption within the country. Regarding crude oil prices, the findings clearly indicate that an increase in oil prices leads to higher renewable energy consumption, while a decrease in oil prices reduces it. These results are expected, as rising oil prices incentivize the country to seek more affordable energy alternatives, such as renewable energy. Conversely, when oil prices decline, oil becomes a more cost-effective option, leading to a decrease in renewable energy use.

It is widely recognized that renewable energy serves as a viable alternative to crude oil. For oil-exporting countries with abundant natural resources, transitioning from fossil fuels to renewable energy is often more feasible due to the availability of advanced technologies. According to basic economic theory on cross-price elasticities, there is a positive relationship between the price of one substitute good and the demand for another. Therefore, an increase in oil prices is expected to positively influence renewable energy consumption, as higher oil prices encourage households and businesses to reduce their oil consumption, adopt energy-efficient technologies, and shift towards renewable energy sources. Additionally, an increase in the price level is likely to discourage renewable energy consumption in Saudi Arabia. As the price level rises, the value of the currency diminishes, leading to a reduction in purchasing power. This decline in purchasing power lowers the overall demand for goods and services, including renewable energy, as consumers and businesses find it more challenging to afford these alternatives.

Based on the findings of this research, one crucial recommendation can be made: as the global oil market is currently oversupplied, leading to a decrease in crude oil prices, it is an opportune time for the Saudi Arabian government to impose a tax on crude oil. The revenue generated from this tax could be allocated to fund renewable energy research, thereby enhancing the country's energy security by reducing its reliance on imported crude oil and positioning renewable energy as the primary energy source for Saudi Arabia in the future. Additionally, the government should allocate more resources toward the development and expansion of renewable energy to increase its share in the national energy mix. Emphasizing the use of less water-intensive renewable energy sources, such as solar energy, particularly in urban areas, is essential to reducing the water footprint in major cities across the country. Furthermore, creating a more efficient infrastructure that relies on renewable energy sources, such as solar and wind energy, along with improved rainwater harvesting systems, will optimize energy production and contribute to sustainable urban development. It is also important to harmonize trade policies with other major renewable energy-producing countries, such as China, India, Brazil, South Africa, and Japan, to reduce trade barriers on renewable energy-related goods. Finally, since an increase in the price index negatively impacts renewable energy consumption, the government should provide incentives for the public, such as lower taxes and reduced electricity utility prices. These measures would encourage industries in Saudi Arabia to adopt more renewable energy sources, ultimately lowering production costs and promoting sustainable economic growth.

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