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How Does Financial Market Development Influence Environmental Sustainability in Saudi Arabia?

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ABSTRACT

The integration of environmental and sustainability goals within Saudi Arabia's financial regulatory framework has received significant attention to enhance green finance initiatives aligned with Vision 2030. By using the ARDL method with FMOLS, DOLS, and CCR estimators, this study investigates the impact of market-based financial development (FMD), GDP per capita (GDP), energy consumption per capita (ENG), and trade openness (TO) on the overall greenhouse gas emissions of Saudi Arabia (EQ) between 1994 and 2020. Our results indicate that financial development and energy consumption are significant contributors to emissions, as per the carbon content of energy and industrial investment. Also, GDP per capita has a positive effect, and trade openness serves as a moderator, reducing emissions over the long term. Short-run dynamics exhibit rapid convergence to the long-run equilibrium as captured in the negative in statistically significant error-correction coefficient. Based on these results, the Saudi government should encourage financial development management, promote energy efficiency, and utilize trade policies, as these factors are significant for reducing emissions and maintaining sustainable environmental performance in Saudi Arabia.

Keywords: Vision 2023, Financial Market Development, Greenhouse Gas Emissions, Green Finance Initiatives, Ecofriendly Investment, Autoregressive Distributed Lag Approach
JEL Classifications: C32, O16, P18, P34,Q1, Q4, Q5

1. INTRODUCTION

Economic development is a gradual and complex process whose outcomes, whether beneficial or detrimental, leave a lasting imprint on the foundational structures of a nation (Naseer et al., 2025; Omri et al., 2019; Shah et al., 2025; Younis et al., 2024; Zakari et al., 2024; Zakari et al., 2021). Whereas its influence is often examined through economic, financial, social, and political lenses, its environmental dimension is equally critical. Saudi Arabia stands at a pivotal juncture in its economic evolution, driven by the ambitious goals of Vision 2030, which aim to diversify the economy beyond oil dependence and foster sustainable economic development (Alhejaili, 2024). A key pillar of this transformation is the development of the financial market, which is projected to mobilize capital, improve investment efficiency, foster sustainable economic growth, and support innovation across sectors. However, the environmental consequences of financial market expansion continue underexplored, mainly in resource-rich economies like Saudi Arabia (Adow, 2024b; Omri et al., 2019). As financial markets expand, concerns arise regarding their environmental implications, particularly in a country where fossil fuels dominate the energy mix. The intersection of financial market development and environmental sustainability is increasingly relevant in the context of global climate change and the drive for green finance investments (Naseer et al., 2025). While financial markets can facilitate investments in environmentally friendly technologies, they may also contribute to environmental degradation through increased industrial activity and energy consumption. This duality presents a complex challenge for policymakers in Saudi Arabia, who must balance economic ambitions with environmental stewardship. The relationship between financial market development and environmental sustainability is complex and multifaceted. On one hand, well-functioning financial markets can facilitate green investments, improve access to clean technologies, and promote environmental awareness through ESG (Environmental, Social, and Governance) scores (Landi et al., 2024). On the other hand, increased financial activity may lead to higher energy consumption, industrial expansion, and carbon emissions, particularly if investments are directed toward traditional, polluting sectors.

This study aims to explore the environmental impact of financial market development in Saudi Arabia, focusing on how financial market mechanisms influence ecological outcomes such as carbon emissions and ecological footprint. Compared with current research, this paper makes a noteworthy contribution to the literature on environmental economics and financial development in three significant ways. First in all, this study employs the autoregressive distributed lag (ARDL) method, which is particularly well-suited for analyzing both short-run and long-run relationships among variables with mixed integration orders. This methodological choice allows for robust estimation even with relatively small sample sizes and provides deeper insights into the dynamic interactions between financial market development and environmental indicators such as CO_2 emissions and ecological footprint. Second, the study draws on a comprehensive dataset spanning from 1981 to 2018, incorporating main financial indicators such as stock market capitalization, credit to the private sector, and financial institutions' depth, alongside control variables like foreign direct investment (FDI), trade openness, and energy consumption. This broad scope enables a nuanced understanding of how financial market expansion interacts with environmental outcomes in the context of Saudi Arabia's evolving economic landscape. Third, by applying the ARDL framework, the paper offers evidence-based insights that are directly relevant to policymakers. It highlights the potential environmental consequences of financial sector reforms and underscores the importance of integrating sustainability considerations into financial development strategies. The insights contribute to the growing body of research on green finance and sustainable development, particularly in emerging economies undergoing structural transformation, such as Saudi Arabia.

Our results indicates that financial development and energy consumption are significant contributors to emissions, as per the carbon content of energy and industrial investment. GDP per capita likewise exerts a positive effect, and trade openness is a moderator and reduces emissions over the long term. Short-run dynamics exhibit rapid convergence towards long-run equilibrium as captured in the negative and statistically significant error-correction coefficient. These results emphasize that the financial development management, promotion of energy efficiency, and trade policy utilization are important for reducing emissions and sustaining sustainable environmental performance in Saudi Arabia.

The remainder of this study is systematized as follows. Section 2 reviews the previous literature, and Section 3 details the data the empirical model specification. Section 4 presents and discusses the empirical results of this study. Section 7 concludes and provides recommendations.

2. LITERATURE REVIEW

Environmental degradation has increasingly attracted the attention of major scientific research, particularly since the onset of accelerated industrial development in the 1970s (Mehmood et al., 2024). According to Humbal et al. (2023), several key factors contribute to this degradation, including urbanization, deforestation, rapid population growth, and industrialization. Over time, human activities have played a substantial role in weakening environmental quality and increasing pollution. Over the time, the pursuit of rapid and unintended industrial growth expected at economic expansion has led to rises in environmental damage. A variety recent studies confirm that financial market development (FMD) in Saudi Arabia contributes to increased CO_2 emissions, particularly in the short run. For instance, Adow (2024b) conducted an asymmetrical analysis of the relationship between financial market development (FMD), foreign direct investment (FDI), and CO_2 emissions in Saudi Arabia from 1970 to 2021. The author indicates that rising financial market development leads to higher emissions due to increased industrial activity, consumer credit expansion, and infrastructure development. Her findings highlights that over 99% of Saudi Arabia's energy consumption is derived from fossil fuels, which exacerbates the environmental impact of financial expansion. Besides, financial market development facilitates access to credit, enabling greater consumption of energy-intensive goods such as vehicles and appliances, thereby increasing emissions. However, the author also notes that financial market development can support green investments and R&D in clean technologies, suggesting a dual role depending on the nature of financial flows. Hence, financial markets can both promote and hinder environmental sustainability depending on the direction of development.

Jiang and Ma (2019) found that financial development significantly increases carbon emissions globally, particularly in emerging markets, because credit expansion boosts demand for energy-intensive goods and industrial activities. Özmerdivanlı and Sönmez (2025) demonstrated that financial development in G7 and E7 economies strongly linked with higher energy consumption and environmental degradation. Their findings agree that easier access to credit stimulates demand for more durable goods such as vehicles, appliances, and housing. By using a nonlinear ARDL model, Raggad et al. (2024) investigate the asymmetric effects of financial development on Saudi Arabia's ecological footprint. The authors revealed that positive shocks in financial market development significantly increase environmental degradation, while negative shocks do not lead to a proportional reduction in emissions. This asymmetry is attributed to structural rigidities and the persistent nature of pollution-intensive investments once initiated. Similarly, Mahmood et al. (2018) confirmed the asymmetric impact of FMD on CO_2 emissions, supporting the

Environmental Kuznets Curve (EKC) hypothesis in the Saudi context. Also, in the context of Saudia Arabia economy, Toumi and Toumi (2019) studied the causality relationship between energy consumption, CO_2 emissions and growth by employing data over the period from 1990 to 2014. The authors agreed the existence of asymmetry in the designated variables. Asongu et al. (2016) examined the association between economic growth, CO_2 emissions and energy use in 24 African economies.

In Saudia Arabia context, Tahir et al. (2024) carried out a comprehensive research study to investigate the determinants behind environmental degradation. Their findings show that urbanization, income, and natural resources have degraded the environment in KSA. Alshammari (2025) examined the role of financial inclusion and found that while it enhances access to capital, it may lead to higher emissions unless directed toward renewable energy projects. The EKC framework was used to demonstrate the turning point of income per capita for environmental improvement. Further, Belloumi and Alshehry (2015) established that energy use and income level are the key driving forces behind increased CO_2 emissions in KSA. Murshed (2022) emphasized the importance of the environment and exhibited that environmental degradation negatively impacts global economic growth. Environmental degradation has multiple adverse consequences for the KSA economy. Therefore, in the first step, it is indeed very important to figure out what exactly causes environmental degradation in the case of KSA economy. The policymakers could in turn formulate suitable policies. Empirical literature is quite rich on the specific relationship between environmental degradation and its main determinants. Some researchers have carried out research studies by focusing on different regions to highlight the main determinants of the degradation of environment. Burki and Tahir (2022) showed that energy consumption and development of financial sector have degraded the quality of environment of ASEAN economies. Their study also tested the validity of the EKC hypothesis and concluded that the actual shape of EKC hypothesis is N-shaped which is indeed a significant contribution in the literature. Similarly, Liu et al. (2022) have focused on the emerging seven (E-7) economies and reported that population growth, economic growth and renewable energy uses enhance CO_2 emissions. Furthermore, in the context of OECD economies, Majeed et al. (2022) showed that manufacturing process contributes positively to CO_2 emissions. Some researchers have focused on different individual economies to highlight the determinants of environmental degradation. Ayobamiji and Kalmaz (2020) have focused on the economy of Nigeria for the period 1971-2015 and reported that energy consumption is positively while FDI is negatively linked with CO_2 emissions. Similarly, in the context of Pakistan economy, Abbas et al. (2020) reported that income, FDI, population and industrialization have mainly worsened the quality of the environment over the years. Furthermore, KOSTAKIS et al. (2017) provide empirical evidence supporting the validity of the EKC hypothesis is for Brazilian and Singapore economy over the period 1970–2017, employing several econometric techniques, including ARDL, DOLS and FMOLS estimators. More recent studies have examined the complex relationship between financial development and environmental sustainability in Saudi Arabia, highlighting country-specific dynamics. The asymmetric nature of the FMD-environment nexus has been substantiated in multiple contexts. Hussain et al. (2023) employed both symmetric and asymmetric ARDL models to analyze the relationship between financial development and CO_2 emissions in Pakistan. Their findings indicate that positive shocks in financial development significantly increase emissions, while negative shocks do not equivalently reduce them. This asymmetry suggests that once financial systems expand and facilitate pollution-intensive activities, reversing these effects is not straightforward due to structural inertia and the "ratchet effect." More recently, Adow (2024b) applied a nonlinear ARDL approach to Saudi Arabia and found that increasing FMD raises emissions, but decreasing FMD does not significantly reduce them, reinforcing the asymmetric hypothesis. The moderating role of FDI in the FMD-environment relationship is gaining scholarly attention. Hasan et al. (2024) explored this dynamic in the Canadian context and found that environmental and regulatory quality significantly influence the ability of financial development to attract sustainable FDI. Their findings suggest that when FDI is directed toward environmentally friendly sectors, it can mitigate the negative environmental impacts of financial expansion. This supports the "Pollution Halo Hypothesis," where FDI brings cleaner technologies and better environmental practices to host countries. In Saudi Arabia, Adow (2024a) observed that while FDI in sectors like transportation and manufacturing tends to increase emissions, FDI in green technologies and renewable energy can have a mitigating effect, highlighting the importance of the sectoral composition of FDI. Recent studies have emphasized the moderating role of FDI in enhancing environmental sustainability in Saudi Arabia. Elimam and Alattas (2025) found that FDI contributes positively to sustainable economic growth, especially when directed toward sectors aligned with Saudi Arabia's Vision 2030, such as renewable energy and green infrastructure. Moreover, Famanta et al. (2024) demonstrated that FDI in environmentally friendly sectors can mitigate the negative environmental impacts of financial development, supporting the Pollution Halo Hypothesis. These findings suggest that the sectoral composition and environmental orientation of FDI are critical in determining its moderating effect on the FMD-environment nexus.

These studies collectively suggest that financial market development in Saudi Arabia has a complex and often contradictory relationship with environmental sustainability. The direction and magnitude of impact depend on factors such as policy orientation, investment channels, and the maturity of financial institutions.

Based on the literature, we propose the following hypotheses:

H_1: Financial market development in Saudi Arabia has a positive impact on CO_2 emissions in the short run due to increased industrial and consumer activity.

H_2: Financial market development contributes to environmental sustainability in the long run by facilitating investments in green technologies and energy-efficient infrastructure.

H_3: The relationship between financial market development and environmental degradation is asymmetric; increases in financial development exacerbate emissions more than decreases mitigate them.

3. METHODOLOGICAL STRATEGY

The following section describes the selected variables, the model specification, the data description and the econometric methodology employed in this study. The present study employs the general model shown in equation (1) to empirically examine the impact of market-based financial development on environmental quality in Saudi Arabia. In this model, EQ_t is used to denote environmental quality, FMD_t is employed to represent the level of financial market development, and CV_t is utilised to denote a set of control variables. This configuration facilitates an assessment of the influence of financial development on environmental quality, whilst concurrently controlling for pertinent economic and structural factors. This ensures the reliability and consistency of the results obtained.

$$EQ_t = f(FMD_t, CV_t) \quad (1)$$

Financial market development increases the depth, access, efficiency, and stability of the markets, and hence facilitates savings mobilisation, improved resource allocation, and efficient risk mitigation (Mohieldin et al., 2019; Parashar and Jaiswal, 2025). A sophisticated financial infrastructure increases economic productivity and lowers transaction costs (Fama, 1970; Levine, 1999). But its cost to the environment is double-edged: It can finance green technologies and sustainable innovation, while it can also finance enhanced energy usage and carbon-intensive business (Li et al., 2025). This means that it needs a true estimation of its net impact, especially in the Saudi Arabian context.

There are three control variables in the study at hand: The under-investigation variables were: Gross domestic product (GDP) per capita, energy consumption and trade openness. Interaction between growth and the environment is analysed with the help of the Environmental Kuznets Curve (Grossman and Krueger, 1991). In Saudi Arabia, an economy structurally anchored in fossil fuels, empirical studies demonstrate complex and often asymmetric relationships between financial development and environmental sustainability. The extant literature, as evidenced by the works of Raggad et al. (2024) and Das et al. (2023) employing the NARDL approach, demonstrates that while decreases in financial development systematically deteriorate environmental quality, increases do not exert a beneficial effect of a symmetrical nature and may even have adverse long-term consequences. This finding is at odds with the positive role of institutional financial development highlighted by Raggad et al. (2024). In a similar vein, Alshammari (2025) corroborates the Environmental Kuznets Curve (EKC) hypothesis within the context of financial inclusion, thereby validating the assertion that financial inclusion amplifies the adverse effect of economic growth on emissions. Conversely, Abro et al. (2023) identify financial development as a constraint on green growth. Collectively, these studies suggest that, in the absence of explicit policy guidance, the maturation of Saudi financial markets alone is insufficient to drive the decarbonisation of the economy. Instead, they advocate for the strategic steering of the financial sector, coupled with enhanced energy efficiency and a selective openness to foreign investment, in order to reverse this dynamic and align economic development with environmental sustainability objectives.

Expanding upon this groundwork, the original model outlined in equation (1) is further developed into equation (2). This improved formulation incorporates GDP per capita, energy consumption (measured in kilograms of oil equivalent per capita), and trade openness, facilitating a more accurate assessment of their combined effects on environmental quality.

$$EQ_t = \alpha + \beta_1 FMD_t + \beta_2 GDP_t + \beta_3 ENG_t + \beta_4 TO_t + \varepsilon_t \quad (2)$$

FMD_t signifies financial market development. GDP_t, ENG_t and TO_t signify constant local currency GDP_t per capita, energy consumption in terms of units of kg of oil equivalent per capita, and trade openness. β_1, β_2, β_3 and β_4 signify the predictive variables' coefficients. ε_t signifies the error term of the model, while the time variable is signed by t. The model, as indicated in Equation (3), recognizes the exponential variances of the value in the data due to logarithmic transformation usage.

$$LogEQ_t = \alpha + \beta_1 LogFMD_t + \beta_2 LogGDP_t + \beta_3 LogENG_t + \beta_4 LogTO_t + \varepsilon_t \quad (3)$$

3.1. Econometric Approach

Autoregressive distributed lag (ARDL) bounds test procedure is used in this analysis to estimate the model of Equation (3) empirically. ARDL method whose usability with small samples and ability to be used with variables having mixed I (0) and I (1) orders of integrations are highly compatible with this research. Before estimation, the stationarity characteristics of the time series were determined through Augmented Dickey-Fuller (ADF) and Zivot-Andrews (ZA) tests with the latter accounting for the possible existence of a single endogenous structural break. The overall ARDL model specification is as shown in Equation (4), whereas the optimal value of lag length is chosen using the Akaike information criterion (AIC). This model enables both short-term responsiveness and long-term equilibrium relationships and cointegration to be examined through the bounds test, thereby providing a firm basis for appreciating the dynamics of Saudi Arabia's macroeconomic landscape.

$$\Delta LogEQ_t = \beta_0 + \beta_1 Log\ EQ_t + \beta_2 Log\ FMD_t + \beta_3 LogGDP_t + \beta_4 LogENG_t + \beta_4 LogTO_t + \sum_{i=1}^{P}\delta_{1i}\Delta LogEQ_i + \sum_{i=1}^{P}\delta_{2i}\Delta LogFMD_i + \sum_{i=1}^{P}\delta_{3i}\Delta LogGDP_i + \sum_{i=1}^{P}\delta_{4i}\Delta LogENG_i + \sum_{i=1}^{P}\delta_{5i}\Delta LogTO_i + \varepsilon_t \quad (4)$$

The bounds' testing technique was used to determine whether a cointegrating relationship existed between the variables. The identification of such a long-run association is a condition for the correct estimation of the long-run coefficients. The null hypothesis is formulated as H_0: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$. On the other hand, the alternative hypothesis is H_1: $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq 0$. After cointegration has been verified, the error correction model (ECM) is drawn up to evaluate the speed at which the system returns to the long-run equilibrium. Equation (5) shows the model.

$$\Delta LogEQ_t = \delta_0 + \sum_{i=1}^{P}\delta_1 LogEQ_{t-i} + \sum_{i=1}^{P}\delta_2 \Delta LogFMD_{t-i} + \sum_{i=1}^{P}\delta_{3i}\Delta LogGDP_{t-i} + \sum_{i=1}^{P}\delta_{4i}\Delta LogENG_{t-i} + \sum_{i=1}^{P}\delta_{5i}\Delta LogTO_{t-i} + \Psi ECT_{t-1} + \varepsilon_t \quad (5)$$

The existence of established cointegration among environmental quality and its determinants suggests the potential for at least a unidirectional causal link between them.

To investigate these dynamic interactions beyond the long-run equilibrium identified by the ARDL approach, a Granger causality test was conducted. Following the procedure established by (Granger, 1969), the test examines causal linkages by assessing the predictive power of past values of one variable for another. The test is implemented through Equations (6) and (7), which specify the causality models. Equation (6) tests the null hypothesis that variable X does not Granger-cause variable Y, while Equation (7) tests the null that Y does not Granger-cause X.

$$Y_t = \varepsilon_0 + Q_1 Y_{t-1} + \cdots + Q_k Y_{t-k} + \varepsilon_1 X_{t-1} + \cdots \varepsilon_k X_{t-k} + \omega_t \quad (6)$$

$$X_t = \varphi_0 + \vartheta_1 X_{t-k} + \cdots + \vartheta_k X_{t-k} + \varphi_1 Y_{t-1} + \cdots \varphi_k Y_{t-k} + \theta_t \quad (7)$$

In order to confirm the reliability and validity of the autoregressive distributed lag (ARDL) model utilized in this research, several diagnostic tests were conducted. Ramsey RESET test for functional form was utilized in determining the stability of parameters in the long run, as well as the cumulative sum (CUSUM) and CUSUM of Squares for structural stability. Serial correlation has been tested in the model through the Breusch-Godfrey LM test, heteroskedasticity has been tested through Breusch-Pagan-Godfrey and ARCH tests, and normality of residuals through Jarque-Bera. To further test the conclusion of the results, the long-run relations were re-estimated through three robust single-equation cointegration methods: Fully modified OLS (FMOLS) that corrects for endogeneity and serial correlation; dynamic OLS (DOLS) which uses leads and lags to correct for the same problems; and canonical cointegrating regression (CCR). Results obtained using these other methods are convergent with each other, and the large evidence on the robustness of the estimated coefficients of the ARDL method is accordingly positively derived.

3.2. Data

In order to offer an empirical evaluation of the econometric model given, the present study utilizes annual time series data from 1994 to 2020, which were chosen following data availability. The use of an annual frequency is suitable since the main statistical data of the chosen variables are mainly released in the format of an annual frequency. Specific indicators used to approximate each variable and respective data sources are mentioned in Table 1.

This research fills a noted gap within the literature by employing a multi-dimensional approach to the measurement of market-based financial development using five alternative proxy indicators. The proxy indicators collectively capture all the essential dimensions along the access dimension; debt markets; equity markets; insurance markets; depth; efficiency; and stability markets. Particularly, equity market stability is measured in terms of volatility of the stock price while insurance industry growth is measured by the insurance penetration rate as the total gross premiums relative to GDP, a measure methodological alignment with Appiah-Otoo and Acheampong (2021). To aggregate these measures into a composite indicator, a composite financial market development index is derived through Principal Component analysis (PCA), adopting the standard procedure of Shahbaz et al. (2016). Stand-alone proxies' evolutionary trends as well as the resulting composite index are depicted in Figures 1 and 2.

As shown in Figure 1, Saudi financial indicators development during 1994-2020 period demonstrates significant evolution of sophistication of financial markets, and cycles that follow economic and oil trend. Financial Market Access Index has evolved steadily since the beginning of the 2000s and shows increased financial inclusion and access to banking and stock markets.

The Financial Market Depth Index followed an upward trend, indicating credit expansion, diversification of financial instruments, and the strengthening of the capital market's role in the Saudi economy.

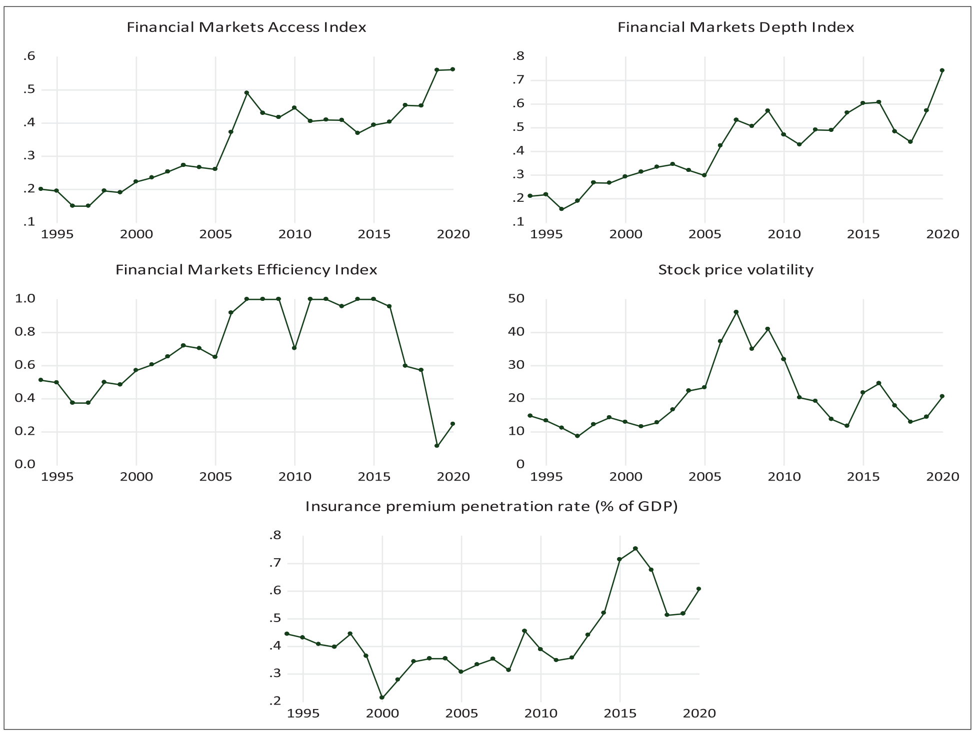
Besides, it is worth mentioning that the financial market efficiency index was on the rise until 2015, after which it sharply dropped. The movement of the indicator manifests a decline of the financial performance of the area which might have been caused, inter alia, by oil shocks and structural reforms. Certainly, between 2005 and 2010 when the market was in a major uproar, stock price volatility was skyrocketing. After that, this volatility has been steady over the last 10 years which might be seen as the development of the financial system becoming more mature gradually. The penetration rate of insurance premiums (expressed as a percentage of GDP) was quite moderate most of the time until the mid-2000s and then it went up steeply after 2010, in a link with the growth of the insurance sector and the economic diversification which was led by the national reforms. Figure 1, in the main, shows a good transformation of the financial system in Saudi Arabia during the period from 1994 to 2020. Expansion of the market and access to it are the two main outstanding features of the system, whereas, the latter two, i.e., efficiency and stability still fluctuate along with the economic and oil-related changes.

According to Figure 2, the evolution of key economic and environmental indicators between 1994 and 2020 highlights

Table 1: Proxies of the study variables

Variables	Measurement	Source of data
EQ	Total greenhouse gas emissions excluding LULUCF (Mt CO_2e). A measure of annual emissions of the six greenhouse gases (GHG) covered by the Kyoto Protocol (carbon dioxide [CO_2], methane [CH4], nitrous oxide [N_2O], hydrofluorocarbons [HFCs], perfluorocarbons [PFCs], and sulphur hexafluoride [SF6]) from the energy, industry, waste, and agriculture sectors, standardized to carbon dioxide equivalent values.	World Bank Database
FMD	Financial market access index Financial market depth index Financial market efficiency index	International Monetary Fund
	Stock price volatility Stock index	Global Financial Development
	Total insurance penetration (% of GDP)	Federal Reserve Economic Data
GDP	GDP per capita (constant LCU)	World Bank Database
TO	Total exports and imports of goods and services (% of GDP)	
ENG	Energy use (kg of oil equivalent per capita)	

Figure 1: Time series plots of the proxy variables for the financial market development



Source: Authors' calculations

contrasting dynamics. Total greenhouse gas emissions increased steadily until 2014, reflecting the intensification of productive activities and a continued reliance on fossil fuels, before stabilising and slightly declining from 2016 onwards.

GDP per capita has an irregular pattern: after plummeting during the 1990s, it slowly recovered 2000s levels, reaching a height in 2018-2019, only to decline in 2020 with the revolutions in the global economy. Trade openness, defined as exports plus imports as a percentage of GDP, rose up to the financial crisis of 2008, then gradually decreased thereafter, indicating a deceleration of international trade.

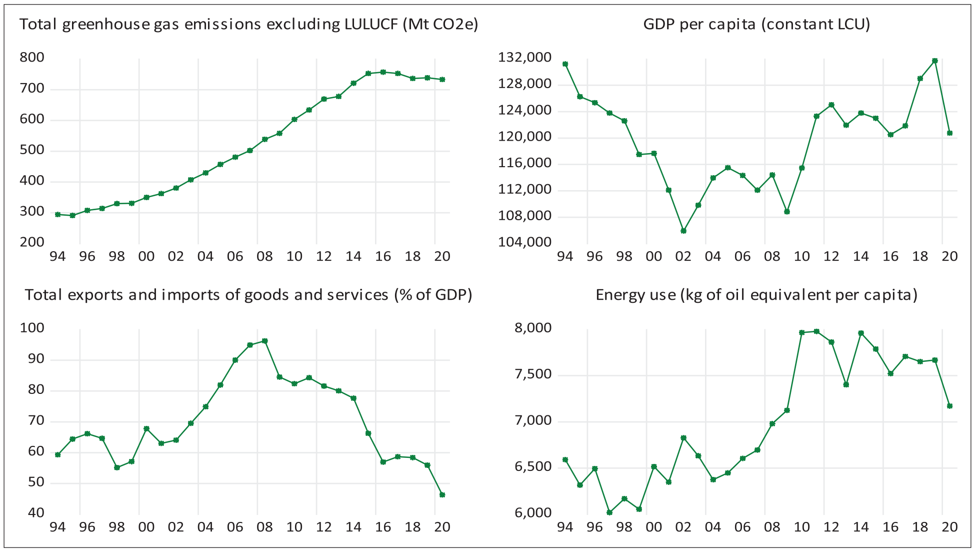
During the same time, per capita consumption of energy increased until 2010, stabilized subsequently, and then declined somewhat after 2016. Figure 2 overall implies that following a period of highly emitting economic and energy expansion, Saudi Arabia is undergoing a transition process to a lower polluting, more efficient energy path, an early decoupling of economic expansion from environmental deterioration.

4. EMPIRICAL RESULTS AND DISCUSSION

The descriptive statistics presented in Table 2 summarise the main characteristics of the dataset, including the mean, median, extremes, standard deviation, skewness, and kurtosis. Most variables exhibit a slight negative skew, indicating a concentration of higher values around the mean, whereas trade openness (Log TO) shows a slight positive skew.

Standard deviations indicate that the four variables, Log EQ, Log GDP, Log ENG, and Log TO, have low dispersion, whereas

Figure 2: Time series plots of the dependent variable and other variables used



Source: Authors' calculation

Table 2: Descriptive statistics

Variables	Log EQ	Log FMD	Log GDP	Log ENG	Log TO
Mean	6.203	0.859	11.690	8.849	−0.367
Median	6.220	1.274	11.701	8.829	−0.412
Maximum	6.630	1.696	11.789	8.985	−0.038
Minimum	5.674	−1.192	11.570	8.703	−0.769
Standard deviation	0.346	0.816	0.057	0.094	0.189
Skewness	−0.151	−1.101	−0.214	0.106	0.019
Kurtosis	1.500	3.491	2.273	1.590	2.166
Jarque-Bera	2.634	5.727	0.801	2.287	0.784
Probability	0.268	0.057	0.670	0.319	0.676
Sum	167.482	23.190	315.628	238.917	−9.911
Sum Sq, deviation,	3.119	17.327	0.085	0.228	0.924

Source: Authors' calculations

Table 3: Correlation matrix

Correlation Probability	Log EQ	Log GDP	Log FMD	Log ENG	Log TO
LogEQ	1.000				

Log GDP	0.155	1.000			
	0.440	-----			
Log FMD	0.846	−0.161	1.000		
	0.000	0.422	-----		
Log ENG	0.890	0.266	0.720	1.000	
	0.000	0.180	0.000	-----	
Log TO	0.096	−0.406	0.289	0.138	1.000
	0.635	0.036	0.144	0.493	-----

Source: Authors' calculations

Log FMD shows higher variability that is due to a few extreme observations. The kurtosis figures indicate that the distributions are mostly normal, and that Log FMD is a bit leptokurtic.

Standard deviations reveal that the variables Log EQ, Log GDP, Log ENG, and Log TO are closely Jarque-Bera tests indicate that the variables do not significantly deviate from normality at the 5% significance level. In general, the data seem to be of good quality and appropriate for further econometric analyses, however, the higher volatility and skewness of Log FMD should be taken into account. The correlation matrix displayed in Table 3 shows that all explanatory variables are positively correlated with greenhouse gas emissions (Log EQ) to different extents. Economic activity (Log GDP) and energy consumption (Log ENG) show positive and significant correlations with Log EQ, suggesting that higher GDP per capita and greater energy use are associated with increased emissions.

Trade openness (Log TO) presents moderately positive but weaker correlation, and market-based financial development (Log FMD) illustrates very weak and insignificant correlation with Log EQ. This indicates that financial development has little direct effect on greenhouse gas emissions and its effect on environmental quality can be indirect, calling for an in-depth econometric analysis. Prior to the time series analysis, it is necessary to identify the order of integration of all variables. This is necessary to prevent spurious regressions and choose an adequate econometric method. For this purpose, two complementarity unit root tests were used: the Augmented Dickey-Fuller (ADF, 1979) and (Phillips and Perron, 1988) tests, along with the Zivot and Andrews (2002) test, which considers the possibility of endogenous structural breaks in the series.

The results of the ADF and PP tests, as indicated in Table 4, reveal that most of the variables, i.e., Log EQ, Log FMD, Log GDP, Log ENG, and Log TO are non-stationary at levels but become stationary upon first differencing, an indication that they are integrated of order one, I (1). The congruence between the two tests reveals that the dataset is of a mixed order of integration, containing both I (0) and I (1) variables. The outcome justifies the use of the ARDL model, which best applies in such a case, as none of the variables are integrated of order two, I (2).

However, time series data can be impacted by structural breaks because of economic, political, or institutional shocks that may result in biased outcomes when traditional unit root tests are applied. To eliminate this limitation, the Zivot-Andrews's test was applied (Table 5) in a manner to endogenously identify both a unit root and a structural break in the series. The results provide some significant breakpoints: 2016 for Log EQ, 2009 for Log FMD, 2010 for Log ENG and Log GDP, and 2006 for Log TO. These break dates coincide with the major economic and institutional events in Saudi Arabia, such as the 2008-2009 global financial crisis, the 2011 political transition, and the subsequent structural and energy sector reforms that ensued.

Overall, the findings confirm that the variables are of mixed orders, I (0) and I (1), and significantly exhibit breaks in structure. The findings reaffirm the suitability of adopting the ARDL method that accommodates the mixed integration nature of the variables as well as detects the short- and long-run dynamics and for the structural changes that may exist in the data. The final selected ARDL model is (3, 2, 2, 3, 3) for Log EQ, Log FMD, Log GDP, Log ENG, and Log TO, as per the Akaike Information Criterion (AIC). The model reflects a good lag structure in order to capture dynamic relationships among the variables so that it can provide strong and reliable long- and short-run estimates. Finally, the bounds test (Table 6) shows that the F-statistic (5.265) exceeds the 1% critical value, which verifies there exists a long-run relationship among Log EQ and the explanatory variables. The result of the long-run bounds test (Table 6) gives that the variables are cointegrated, meaning there is a stable equilibrium in direction to which they converge through time.

The long-term results presented in Table 7 indicate that market-based financial development (Log FMD), economic activity (Log GDP), and per capita energy consumption (Log ENG) have a positive and significant impact on total greenhouse gas emissions in Saudi Arabia. Specifically, a sustained 1% increase in financial development raises emissions by 0.302%, reflecting the role of finance in supporting carbon-intensive industrial and energy investments before green spillovers materialise.

The economic activity contributes to an even greater extent (+1.286% for a 1% rise in per capita GDP), demonstrating the high dependence of the Saudi economy on energy-intensive industrialisation and fossil fuel. Energy consumption per capita is still a very significant factor in the increase of emissions (+1.299%), which energy intensity appears to be one of the major pillars of pollution. On the other hand, foreign trade (Log TO) has a considerable negative impact on emissions (-0.317%), which can be accounted for by the import of clean technology, the implementation of global environmental standards, or the export of clean industrial practices through trade.

The findings reveal that economic and financial development with a significant energy consumption increase the environmental pressures in the case of Saudi Arabia. Nevertheless, trade openness plays the role of a moderator to make the transition towards cleaner activities easier. The measure of total greenhouse gas emissions (EQ) in Saudi Arabia visually presents large changes as a result of transitional dynamics when looking at the short term (Table 8). The coefficient of the error correction term (CointEq[−1] = −0.863, 1% significant) reflects that 86% of the past disequilibria are adjusted within one period, therefore, showing a fast approach to the long-term equilibrium. Immediate changes in financial development (ΔLogFMD) temporarily increase emissions by 0.12% for a 1% change, suggesting that financial expansion stimulates short-term carbon-intensive industrial and energy investments before its positive effects on the green transition materialise.

The negative lag effect of −0.086 reflects the corrective adjustment regarding the postponed realization of greener projects and the gradual improvement toward clean technologies. Economic activity (ΔLog GDP) adds 0.94% more emissions to a 1% change, with a correcting adjustment of −0.48%, indicating that increased economic activity, which is mostly based in the oil and industrial sectors, has a direct environmental impact, which can be reduced somewhat through regulatory measures by government or gains in energy efficiency.

Per capita consumption of energy (ΔLog ENG) increases emissions directly by 0.46%, with subsequent large changes in subsequent years (−0.67% and −0.52%), highlighting that wasteful consumption of fossil fuels is one of the primary drivers of emissions, while the use of more efficient forms of energy or

Table 4: The results of the unit root test

Variable	Level		1st difference		Order of integration
Augmented Dickey-Fuller (ADF)					
	t-statistic	Prob	t-statistic	Prob	
Log EQ	−1.084	0.911	−4.092	0.018	I (1)
Log FMD	−1.175	0.893	−8.587	0.000	I (1)
Log GDP	−2.364	0.388	−6.077	0.000	I (1)
Log ENG	−2.437	0.353	−4.064	0.020	I (1)
Log TO	−0.113	0.991	−3.927	0.026	I (1)
Phillips-Perron (PP)					
Variable	**Level**		**1st difference**		**Order of integration**
	t-statistic	Prob	t-statistic	Prob	
LogEQ	−0.164	0.990	−4.151	0.016	I (0)
Log FMD	−2.525	0.314	−7.167	0.000	I (0)
Log ENG	−2.452	0.346	−6.077	0.000	I (0)
Log GDP	−2.387	0.377	−4.064	0.020	I (0)
Log TO	−0.075	0.992	−3.516	0.059	I (0)

Source: Authors' calculations

Table 5: Zivot-Andrews test results

Variables	(Level)			(First difference)			Order of integration
	DSC	t-stat	P-value	DSC	t-stat	P-value	
Log EQ	2016	−4.084	0.000	2011	−3.652	0.007	I (0)
Log FMD	2009	−5.212	0.003	2010	−4.503	0.007	I (0)
Log ENG	2010	−5.039	0.000	2012	−7.401	0.040	I (0)
Log GDP	2003	−3.987	0.026	2013	−4.823	0.084	I (1)
Log TO	2009	−2.733	0.000	2006	−5.465	0.044	I (1)

Source: Authors' calculations

Table 6: The results of the long-run bound test

F-statistic	5.264946	Critical values (%)	I (0)	I (1)
		10	2.2	3.09
K	4	5	2.56	3.49
		2.5	2.88	3.87
		1	3.29	4.37

Source: Authors' calculations

Table 7: The long-run coefficients

Variable	Coefficient	Standard error	t-statistic	Prob.
Log FMD	0.302*	0.015	19.623	0.000
Log GDP	1.286*	0.195	6.604	0.001
Log ENG	1.299*	0.119	10.946	0.000
Log TO	−0.317*	0.059	−5.356	0.002
C	−20.693*	1.893	−10.930	0.000

R-squared: 0,999, Adjusted R-squared: 0.998, F-statistic: 1122,124 (0.000). ***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively. Source: Authors' calculations

Table 8: The short-run coefficients

Variable	Coefficient	Standard error	t-statistic	Prob.
D (Log EQ [−1])	0.879*	0.149	5.897	0.001
D (Log EQ [−2])	0.425**	0.152	2.801	0.031
D (Log FMD)	0.124*	0.016	7.798	0.000
D (Log FMD [−1])	−0.086*	0.012	−7.000	0.000
D (Log GDP)	0.940*	0.116	8.125	0.000
D (Log GDP [−1])	−0.479*	0.073	−6.535	0.001
D (Log ENG)	0.461*	0.069	6.712	0.001
D (Log ENG [−1])	−0.668*	0.113	−5.915	0.001
D (Log ENG [−2])	−0.520*	0.090	−5.802	0.001
D (Log TO)	−0.180*	0.033	−5.468	0.002
D (Log TO [−1])	0.156*	0.030	5.264	0.002
D (Log TO [−2])	0.216*	0.041	5.305	0.002
Coint Eq (−1)*	−0.863*	0.113	−7.610	0.000

R-squared: 0.960, Adjusted R-squared: 0.917. ***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively. Source: Authors' calculations

renewable energies can mitigate such pressures in the long run. Foreign trade (ΔLogTO) first decreases emissions by 0.18% but then gradually leads to positive effects (+0.16% and +0.22%) for the lags, which indicates a combination of imported cleaner technologies and exported energy-consuming products and puts a spotlight on the lagged environmental impact of trade.

The model, in general, is strong, as evidenced by the R^2 value of 0.960 and the adjusted R^2 of 0.917, which is a clear indication of the model's high explanatory power. So, short-term emissions in Saudi Arabia are very much influenced by economic, financial, and energy-related shocks, after which the adjustment processes take over to gradually restore equilibrium at the long-term level, thus emphasizing the necessity of integrated policies that intertwine financial development, energy transition, and economic management for emissions control.

The Granger causality test outcomes in Table 9 indicate the directional relationships between total greenhouse gas emissions (LOGEQ) and the explanatory variables in Saudi Arabia. In the short term, financial development (LOGFMD) does not lead to a significant increase in emissions; however, a weak bidirectional causality is found, which implies that emissions may also some

Table 9: Results of the granger causality test

Null hypothesis	F-statistic	Prob,
LogFMD does not Granger Cause LogEQ	3.295**	0.083
LogEQ does not Granger Cause LogFMD	4.066***	0.056
LogGDP does not Granger Cause LogEQ	18.773*	0.000
LogEQ does not Granger Cause LogGDP	2.644	0.118
LogENG does not Granger Cause LogEQ	0.536	0.472
LogEQ does not Granger Cause LogENG	6.143**	0.021
LogTO does not Granger Cause LogEQ	19.962*	0.000
LogEQ does not Granger Cause LogTO	5.085	0.034

Source: Authors' calculations

Table 10: Results of diagnostic and stability tests

Diagnostic and stability tests	F-statistic	Prob. F (2,11)
Breusch-Godfrey serial correlation LM test	5.342	(0.101)
Heteroskedasticity test: Breusch-Pagan-Godfrey	0.825	(0.652)
Jarque-Bera	1.109	(0.574)
Ramsey RESET test	0.013	(0.986)

Source: Authors' calculations

extent cause financial development, maybe as a result of the impacts of green financing policies.

The economic activity (LogGDP) shows a significant one-way causality to emissions, which means that a growing economy that is mostly dependent on the industrial and energy sectors is the main driver of emissions directly without any immediate feedback effects. Energy consumption (LogENG) is not a Granger cause of emissions, while (LogEQ) has an impact on (LogENG), which indicates that emission intensity can become a factor of energy demand in polluting sectors. In summary, foreign trade (LogTO) and emissions are the main factors showing a significant bidirectional relationship, indicating the decrease of emissions caused by trade through technological imports and changes of the industrial structure, as well as the increase of emissions caused by trade through the setting of environmental standards and competitiveness.

These findings indicate that, in the short term, economic activity and foreign trade are the dominant drivers of emissions, with energy consumption and financial development exerting more complex and lagged effects, illustrating the multiplicative interdependencies between the economy, finance, energy, and the environment in Saudi Arabia. Diagnostic tests presented in Table 10 present evidence of the validity and consistency of the estimated model. Breusch-Godfrey serial correlation LM test (F = 5.342, P = 0.101) confirms the absence of serial correlation among the residuals, thereby the error terms become independent.

The Breusch-Pagan-Godfrey test for heteroskedasticity (F = 0.825, P = 0.652) validates the homoskedasticity and the validity of the estimated coefficients, as the variance of the residuals is homogeneous. The Jarque-Bera normality test (JB = 1.109, P = 0.574) validates the normal distribution of the residuals, which in turn is a precondition for the validity of the statistical inference. Finally, the Ramsey RESET specification test (F = 0.013, P = 0.986) confirms that the model is correctly specified and that no hidden variable has been omitted. Overall, these results indicate that the model is statistically significant and robust and that the estimated coefficients can be relied upon when analysing the determinants of Saudi Arabian greenhouse gas emissions.

The CUSUM and CUSUM-squared tests for stability also confirm that the estimated model is stable both in the short and long term because the test statistics lie within the 5% confidence limits. The graphical plots of Figures 3 and 4 indicate that the estimated coefficients have no significant structural breaks for the period 2015-2020. Figure 3 presents the CUSUM test results, where the cumulative sum statistic (blue line) is well away from crossing the 5% significance bounds (dashed lines) along the way, indicating coefficient stability and no meaningful structural changes in relationships among variables. Further, Figure 4 shows the CUSUM of squares result, and it is noticed that the statistic stays within confidence limits, thereby confirming the stability of the residual variance and the overall structural stability of the model. Briefly, the findings of these tests for stability provide very strong evidence that the ARDL model is econometrically sound, its parameters are stable for the entire sample period, and the interpretation of long- as well as short-run dynamics can be considered statistically credible.

Thus, the model parameters exhibit temporal stability, confirming the robustness and reliability of the econometric findings. In conclusion, the results indicate that economic GDP per capita and energy consumption are the main short-term drivers of greenhouse gas emissions in Saudi Arabia, whereas financial development when channelled towards environmentally sustainable investments can foster environmental sustainability in the long run. This outcome is consistent with Saudi Arabia's economic structure, where growth is generally associated with the expansion of energy-intensive industries and a rise in the use of fossil fuels. Therefore, a slowdown of the economy is rarely seen and usually the energy demand gets amplified first and then carbon emissions follow. Nevertheless, a carbon finance can offset the growth effect if investments in clean energy solutions, technological innovation, and energy efficiency are prioritized.

Basically, the figured-out model is statistically strong, steady, and suitable, thus it is a significant factor in the trustworthiness of the results and their policy impact in the creation of successful environmental and financial strategies. In addition to the diagnostic and stability tests referred to above, robustness checks were done by re-estimating the model with FMOLS, DOLS, and CCR methods. The outcomes of these estimations, which are shown in Table 11, are compared with the long-run coefficients obtained from the ARDL model (Table 6).

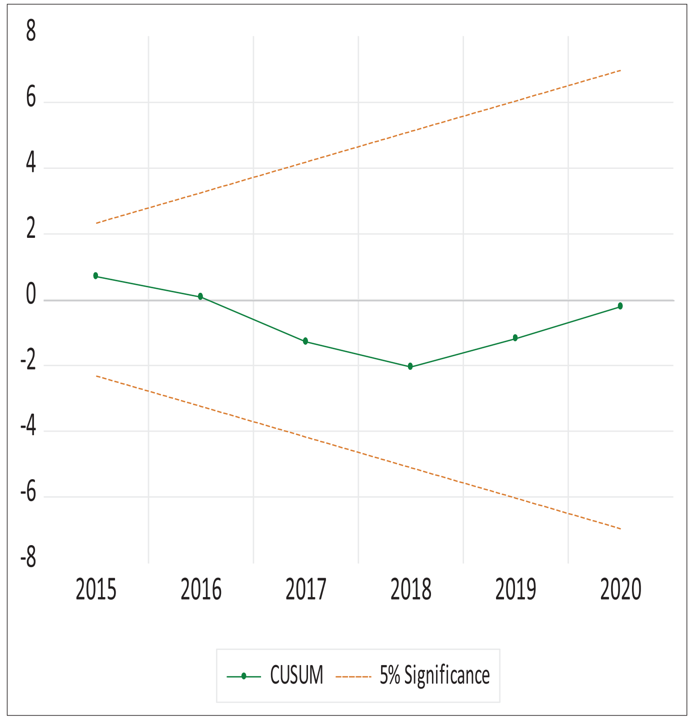
Table 11: Estimates by FMOLS, DOLS, and CCR

Variable	FMOLS	Prob	DOLS	Prob	CCR	Prob
Log FMD	0.037*	0.000	0.327*	0.000	0.250*	0.000
Log GDP	0.572	0.201	1.267*	0.001	0.457	0.248
Log ENG	1.746*	0.000	1.088*	0.001	1.707*	0.000
Log TO	0.106	0.207	−0.199*	0.003	−0.228***	0.053
C	−16.166*	0.001	−18.552*	0.000	−14.525*	0.001
R^2	0.924		0.999		0.920	
Adj, R^2	0.910		0.995		0.905	

***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' calculations

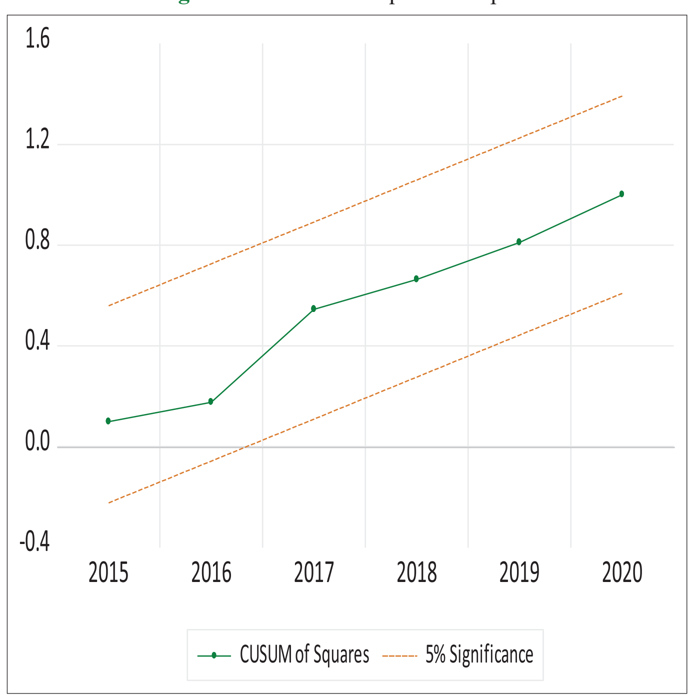
The long-run coefficients from FMOLS, DOLS, and CCR also indicate that market-based financial development (Log FMD) and per capita energy consumption (Log ENG) have a statistically significant positive impact on greenhouse gas emissions in Saudi

Figure 3: CUSUM test plots



Source: Authors' calculations

Figure 4: CUSUM of squares test plots



Source: Authors' calculations

Arabia, thus providing evidence in support of the ARDL findings. From a financial point of view, this means that the development of financial markets in Saudi Arabia has been a major factor in the carbon-intensive sectors' growth, such as energy production, petrochemicals, and heavy industry.

While these sectors are major contributors to growth and diversification, they are still largely dependent on fossil fuels, therefore, the positive correlation between financial development and emissions is strengthened. The considerable effect of per capita energy consumption is in line with the country's energy profile, where carbon emissions are directly increased as energy use grows due to the dependence of electricity generation and industrial activities on oil and natural gas. Economic activity (Log GDP) has similarly a positive and statistically significant impact, mainly under the DOLS method, which indicates the structural dependence of Saudi Arabia on energy-intensive and industrial sectors. The link between these two only somewhat supports the environmental Kuznets curve hypothesis as economic growth is still linked to high emissions at the present stage of development.

However, the impact of foreign trade (Log TO) on the environment is somewhat ambiguous: FMOLS indicates a positive but statistically insignificant relationship, DOLS a significant negative impact, and CCR a small negative effect - suggesting that the multidimensional nature of the trade effect on environmental outcomes is still there. The variation of studies results can be related to the situation, that on one hand the export of Saudi Arabia is the reason for the rise of emissions, however on the other hand the import of clean technology and capital goods is mitigating some of the impact.

As a whole, these results back up the power and reliability of the ARDL results in confirming that financial development and energy consumption are the main causes of emissions while foreign trade is a hidden and moderating factor. From a policy perspective, one of the main consequences of these results is that the alignment of financial market reform with green investment objectives, as well as energy diversification policies, is what will enable the Saudi economy to reduce its carbon emissions.

5. CONCLUSION AND POLICY IMPLICATIONS

This study employs ARDL approach and supported by FMOLS, DOLS, and CCR estimations to examine the factors contributing to climate-altering gas emissions in the kingdom of Saudi Arabia covering 1994-2020 period. The variables considered include environmentally friendly financial development, economic activity, energy use per capita, and openness to trade. The empirical results reveal that financial development and energy consumption are the determinants of emissions, and economic activity also positively affects it.

Meanwhile, the openness of trade has a moderating impact that lessens the pollution in the distant future. The short-term changes show a quick transition to long-term balance, which is the reflectivity of emissions being very reactive to economic, financial, and energy shocks.

These insights can lead to significant policy changes in people's lives. The foundation of any attempt to mitigate the environmental consequences of economic growth should be the promotion of green investments and low-carbon technologies in a sustainable manner, through financing growth. A large part of the carbon emissions can be limited without a decrease in activities by raising energy efficiency and fast-tracking the transition to renewable energy sources. Trade policy should, therefore, focus on facilitating the import of cleaner technologies and more environmentally friendly practices to enhance the positive effects of openness. In essence, a concertedly financed strategy comprising monetary regulation, energy transition, and trade policy is instrumental in achieving sustainable economic growth and controlling greenhouse gas emissions in Saudi Arabia.

This study provides important insights for both investors and policymakers in Saudi Arabia, particularly in aligning financial market development with environmental sustainability under Vision 2030. For investors, it is crucial to monitor short-term risk dynamics between the carbon market and financial instruments, especially during periods of intensified climate policies, and to dynamically adjust investment portfolios to mitigate short-term market volatility. Stable segments of the hydropower and carbon markets can serve as effective risk absorbers, offering opportunities to hedge risks while accounting for shifts in risk roles across different time horizons.

For policymakers, strengthening the regulation and coordination of the carbon market with the power industry is crucial, including improvements to trading rules, stock market liquidity, and risk management outlines. Promoting renewable energy development (e.g., wind and solar power), through targeted research and development support, can be optimize subsidy strategies, and heightened market competitiveness. Also, it can reduce reliance on carbon-intensive thermal power and contribute to long-term emission reductions. Additionally, establishing multi-scale climate risk response mechanisms is crucial, combining short-term emergency plans for acute events such as floods or typhoons with long-term adaptation strategies for chronic risks such as sea-level rise.

Finally, coherent green transition policies that integrate climate risk management, financial market development, and sustainable investment frameworks are necessary to maintain market stability and support Saudi Arabia's carbon neutrality objectives over the long term.

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